spectroscopic evidence of charge exchange X-ray emission from galaxies
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What are the origins of the soft X-ray line emission from non-AGN galaxies? XMM-Newton RGS spectra of nearby non-AGN galaxies (including starforming ones: M82, NGC 253, M51, M83, M61, NGC 4631, M94, NGC 2903, and the Antennae galaxies, as well as the inner bulge of M31) have been analyzed. In particular, the Kα triplet of O vii shows that the resonance line is typically weaker than the forbidden and/or inter-combination lines. This suggests that a substantial fraction of the emission may not arise directly from optically thin thermal plasma, as commonly assumed, and may instead originate at its interface with neutral gas via charge exchange. This latter origin naturally explains the observed spatial correlation of the emission with various tracers of cool gas in some of the galaxies. However, alternative scenarios, such as the resonance scattering by the plasma and the relic photo-ionization by AGNs in the recent past, cannot be ruled out, at least in some cases, and are being examined. Such X-ray spectroscopic studies are important to the understanding of the relationship of the emission to various high-energy feedback processes in galaxies.

1 Introduction

Soft X-ray line emission has commonly been used to trace various types of galactic feedback in nearby starburst and normal galaxies. Assuming an origin of this emission in optically thin thermal (collisionally excited) hot plasma, one may further estimate its mass, energy, and chemical contents and even its outflow rate from such a galaxy. However, the X-ray emission can be seriously contaminated, if not dominated, by various other contributions. They must be quantified before we can reliably use the emission to study the galactic feedback and its impact on the galactic ecosystem.

Here we focus on the evidence of a significant contribution from charge exchange (CX, also called charge transfer) X-ray emission at interfaces between hot and cool gases in galaxies. In the simplest form, a CX can be represented by

\[ A^{q+} + N \rightarrow A^{(q-1)+} + N^+ , \]  

(1)

where a highly ionized ion \( A^{q+} \) (like O viii or Ne x) picks up an electron from a neutral species \( N \) (like H, H2, or He), producing an excited ion \( A^{(q-1)+} \), which then decays to the ground state, emitting X-ray photon(s). Extensive studies have been carried out on the solar wind CX (see Dennerl 2010 for a recent review). In particular, the solar wind CX origin of the X-ray emission from comets has been established spectroscopically. The solar wind CX with the local interstellar medium may also account for a substantial part of the observed soft X-ray background (e.g., Koutroumpa et al. 2011). Furthermore, the CX has been speculated to be important in many other types of astrophysical objects (e.g., Lallement 2004) and has specifically been proposed to be responsible for emission features unaccounted for by thermal plasma modeling alone in X-ray CCD spectra of Galactic supernova remnants (e.g., Katsuda et al. 2011) and giant H II regions (e.g., Townsley et al. 2011). Such CX scenarios, if confirmed spectroscopically, could provide new insights into the physical, chemical, and kinematic properties of the underlying hot plasma and its interplay with cool gas.

The most straight-forward X-ray spectroscopic diagnostic of a significant CX contribution is the so-called G ratio [= \(( f + i)/r \), forbidden + inter-combination to resonance lines] of the Kα triplets of He-like ions. Take O vii as an example. For an optically thin thermal plasma with a temperature of a few \( 10^6 \) K and in collisional ionization equilibrium, G should be considerably less than one (Porquet et al. 2001). The temperature may be constrained independently, for example, by the resonance transition ratios of H-like to He-like ions (e.g., Liu et al. 2011).

The only available instruments that allow for such X-ray spectroscopy of moderately extended X-ray-emitting regions are the XMM-Newton Reflection Grating Spectrometers (RGSs), which have both a large effective area and a large dispersion power. XMM-Newton observations, with a spatial resolution of \( \sim 6'' \) (FWHM) at \( \sim 1 \) keV, are typically carried out with simultaneous exposures by the two co-aligned RGSs, together with the European Photon Imaging Cameras (X-ray CCDs). The orientation of the satellite determines the dispersion direction of the RGSs, which are slit-less spectrometers and are sensitive to photons in the
0.3-2 keV range. For a point-like source, the spectral resolution of the RGSs is $\lambda/\delta \lambda \sim 400$ (HEW) at $\sim 20$ Å. For an extended region, one can obtain useful 1-D spatial information over the cross-dispersion range of $5'$ wide. In the dispersion direction, the RGSs cover the entire field of view of the telescope mirrors. The extent of the region translates to an apparent (1st-order) wavelength shift of 0.14 Å arcmin$^{-1}$ with respect to a non-displaced source. Therefore, for a region with a moderate extent (e.g., $< 2'$), the spectral resolution of an integrated RGS spectrum can still be substantially better than that of X-ray CCD data. In fact, the wavelength shift can sometimes be used to extract the spatial information along the dispersion direction.

2 Examples

2.1 M31 Bulge

Our existing study of the central bulge of M31 (e.g., Fig. 1) demonstrates the spectroscopic diagnostic power of RGS observations in probing the nature of the soft X-ray line emission (Liu et al. 2010). Fig. 1c, for example, shows a clear intensity excess of the observed spectrum above a simple thermal plasma model fit at $\sim 22$ Å. This excess is apparently due to the prominence of the forbidden line (at 22.1 Å) with respect to the resonant one (21.6 Å) of the He-like O vi Kα triplet. Furthermore, the excess is shown to be present throughout much of the cross-dispersion range of the RGS observations and seems to correlate well with the distribution of the cool gas, as traced by the Hα emission (Fig. 1a: Liu et al. 2010). In addition, the centroid of the Ne xi Kα triplet is also closer to its forbidden line wavelength than to its resonant one (Fig. 1b). A natural explanation of these results is that the excess represents the contribution from the CX between the two gas phases. The presence of the diffuse hot gas in the bulge is expected from the stellar feedback in forms of mass loss and Type Ia SNe of low-mass stars (e.g., Tang et al. 2010). There is little evidence for any recent massive star formation in the bulge or even in-falling cool gas clouds/filaments (e.g., Strickland & Stevens 2000; Bauer et al. 2007). Temperature and abundance anomalies have also been reported for starburst galaxies when diffuse X-ray emission is modeled with thermal plasma alone. As demonstrated above, the modeling of the thermal emission alone is not adequate and that other contributions or effects need to be accounted for in order to reliably characterize the properties of the superwinds (e.g., Liu et al. 2011).

3 Implications

Determining the origin(s) of the soft X-ray line emission is important for understanding the galactic feedback, hence the evolution of galaxies. Take nuclear starbursts as an example, which can drive so-called superwinds and have substantial impacts on galactic ecosystem and possibly even on the surrounding intergalactic medium. However, it remains controversial as to whether the observed diffuse soft X-ray emission around starburst galaxies represents the superwinds themselves or just their interfaces with entrained or even in-falling cool gas clouds/filaments (e.g., Strickland & Stevens 2000; Bauer et al. 2007). Temperature and abundance anomalies have also been reported for starburst galaxies when diffuse X-ray emission is modeled with thermal plasma alone. As demonstrated above, the modeling of the thermal emission alone is not adequate and that other contributions or effects need to be accounted for in order to reliably characterize the properties of the superwinds (e.g., Liu et al. 2011).

If the CX is indeed significant, it will then be essential to quantify its contribution. In contrast to the thermal emission, the CX contributes only lines. If an X-ray spectrum arising even partly from the CX is modeled with thermal emission only, then the inferred temperature and chemical properties of the plasma could be grossly wrong. To measure the plasma properties more accurately, one needs to decompose the CX and thermal contributions, spectroscopically. While our existing studies are based chiefly on the G ratios of the Kα triplets of He-like ions (mostly O vi; e.g., Liu et al. 2010, 2011, 2012), jointly fitting multiple emission lines or even an entire spectrum will maximize the use of the spectroscopic information available in the RGS data to effectively test the CX model, to tightly constrain multiple model parameters with proper error propagation, and to decompose the thermal and CX contributions. In a joint analysis, even spectral lines that are not individually detected can be useful, as demonstrated in existing X-ray absorption line spectroscopy (e.g., Yao & Wang 2005; Wang et al. 2009).
et al. 2010 and references therein). Such an analysis will become possible with the upcoming CX spectral model (see the presentation by Smith et al. in this workshop). A joint analysis can, in principle, provide us with unique diagnostics of the hot plasma and its interplay with cool gas. The local emissivity of the CX (assuming single electron capture) is \( \sim n_{A^+} n_{\text{HeII}} v_r \sigma \), where \( n_{A^+} \) and \( n_{\text{HeII}} \) denote the ion and neutral atom densities, while \( v_r \) and \( \sigma \) are their relative velocity and CX cross-section. The \( n_{A^+} \) values of relevant ions (e.g., \( \text{O vii} \) and \( \text{Ne x} \)) depend on the total particle density, metal abundance, and ionization temperature of the hot plasma. These parameters can thus be inferred from the emission line intensities of various ion species. Moreover, the relative intensities of multiple transitions of same ion species are also sensitive to \( v_r \) (e.g., Greenwood et al. 2004). Therefore, the modeling of the CX contribution can be a powerful tool in probing the thermal, chemical, and kinematical properties of the hot plasma.

### 4 Potential Complications

While the CX appears to be an important mechanism in generating soft X-ray line emission, we also need to consider other plausible scenarios in various circumstances. One of such scenarios is the resonance scattering of emission line photons by the X-ray-emitting plasma itself (e.g., Porquet et al. 2001). Such scattering re-distributes optically thick line photons to outer regions. This effect on the spatial distribution of the \( \text{Fe xvii} \) \( 2p - 3d \) transition has clearly been shown with the RGS observations of a few giant elliptical galaxies (Xu et al. 2002; Werner et al. 2009). However, the effectiveness of the scattering is not clear in low \( L_X / L_K \) spheroids (e.g., the bulge of M31), which contain hot plasma of relatively low density, or in starburst galaxies, where hot superwinds are expected to have large velocity dispersions. Our preliminary estimates indicate that the scattering of the \( \text{O vii K} \alpha \) and \( \text{O vii Ly}\alpha \) resonance lines could be significant in the inner bulge region of M31, depending largely on how small the bulk and turbulent velocities of the plasma are. We are currently conducting detailed simulations to determine the significance of the resonance scattering, which may incidentally place constraints on the plasma velocities. If the resonance scattering is important, then one may expect to observe a systematic decreasing \( G \) ratio with increase distances from galaxy central regions. But this effect is not apparent in the existing data (Liu et al. 2012), although a thorough analysis is yet to be performed. The effect could also be diminished if scattered photons are largely absorbed by cool gas. This complication also needs to be investigated.

Large \( G \) ratios can further be produced by plasma under a non-equilibrium ionization condition. Such a condition may be created in a cooling superwind due to fast adiabatic expansion, for example (e.g., Li et al. 2006). The delayed recombination of highly ionized ions in the plasma tends to occur primarily in outer regions of a starburst galaxy. But the large \( G \) ratio is observed in inner regions of galaxies (Liu et al. 2010, 2012). The recombination scenario also does not explain the good correlation of the X-ray emission with the cool gas tracers. A similar condition, however, may also be produced by AGNs. Our sample selection of non-AGN galaxies should have minimized this complication (Liu et al. 2012). We have even avoided the inclusion of galaxies with significant Seyfert 2 nuclei, which could contribute to diffuse soft X-ray emission via photo-ionization and/or scattering. However, there might be significant contributions from AGN relics in some galaxies. We are modeling the emis-
Fig. 2  Fluxed RGS spectra of the central region of M51 (a; with a total effective exposure of 97 ks) and the Antennae galaxies (b; 172 ks). Spectral bins with no exposure (e.g., due to the RGS CCD gaps) are marked with bars at the wavelength axis. Positions of key lines or recombination edges are marked.

Fig. 3  (a) Fluxed RGS spectrum of M82 extracted from a central 1′ region (Liu et al. 2011; see also Ranalli et al. 2008). The continuum is mainly due to X-ray binaries. (b) Close-up of the O VII Kα triplet (Liu et al. 2011). A continuum, which is interpolated between the line wings, has been subtracted. [Figures are reproduced from Liu et al. (2011)]
A relic should show the so-called recombination continuum (or edges; e.g., Guainazzi & Bianchi 2007), whereas the CX should not.

In addition to the spectral analysis and modeling, spatially resolved information also needs to be fully explored. For example, Fig. 4 shows a preliminary version of 2-D X-ray line emission images of M82, reconstructed from the RGS observations. The comparison of such spatial distributions of various emission lines will provide new tests of the scenarios.

Ultimately, we probably also need as much information as can be extracted from data in other multi-wavelength observations to understand the complex high-energy phenomena and processes involved in the heating, transportation, and cooling of the hot plasma and in its interaction with cool gas in galaxies.

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