Astrophysical plasma modeling of the hot Universe : advances and challenges in high-resolution X-ray spectroscopy

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Summary

Hot astrophysical plasma is ubiquitous in the Universe, from comets in our Solar system to the largest scale structures – the cosmic web filaments. These hot plasmas, with temperatures of a few million of degrees, are often observed in the X-ray wavelength range. Spectroscopic diagnostics enable us to probe physical properties like temperature, density, abundance, microscopic turbulence, line of sight velocity, etc. High spectral resolving power is essential to overcome the confusion caused by unresolved spectral features. Thanks to the grating spectrometers aboard *XMM-Newton* and *Chandra*, our knowledge of the hot and energetic Universe is advanced. On the other hand, high quality spectra from current and future generations of X-ray spectrometers also challenge plasma models that are widely used in the community.

Plasma model

To interpret the spectra in a self-consistent way, we need plasma models built on an extensive atomic database. Different plasma models suitable for different astrophysical scenarios are required. For instance, plasmas exposed to a strong external radiation field (e.g. circumnuclear media of active galactic nuclei) require a plasma model in photoionization equilibrium, while low-density high-temperature thermal plasmas (e.g. intracluster media of relaxed galaxy clusters) require a plasma model in collisional ionization equilibrium. In this thesis, we use the SPEX package.

SPEX is a software package optimized for the analysis and interpretation of high-resolution cosmic X-ray spectra. Based on a single atomic database, plasma models provided by SPEX cover a wide range of astrophysical environments. The CIE model is designed for plasmas in collisional ionization equilibrium. The PION model is suitable for plasmas in photoionization equilibrium. The NEIJ model can be applied to the non-equilibrium ionization plasmas. The CX model accounts for charge exchange recombination at the interface between hot and cold plasmas.

Photoionized circumnuclear media

Circumnuclear media of active galactic nuclei can be photoionized by the AGN and they are observed both in absorption and emission in high-resolution spectra. Photoionized outflows are of particular interest since they can influence their nuclear and local galactic environment.

Self-consistent photoionization modeling is the key to properly interpret the intrinsic broad band continuum and all the obscuration, absorption, emission, and extinction effects simultaneously.

Chemical evolution RGS sample

The hot X-ray halos of groups and clusters of galaxies are collisionally ionized. Their line-rich spectra show metal enrichment. The elemental abundances in these collisionally ionized media are footprints of time-integrated yields of various stellar populations. Specific abundance patterns have been left prior to and during the

evolution of groups and clusters of galaxies.

Thanks to the Chemical evolution RGS sample (CHEERS) observed with the Reflection Grating Spectrometer (RGS) aboard *XMM-Newton*, we are able to understand the chemical enrichment of various elements in nearby ellipticals, groups, and clusters of galaxies. Low- and intermediate-massive stars in the asymptotic giant branch are the main metal factories of light elements like nitrogen. Massive stars undergo core collapse at the end of their evolution ejecting a large amount of α-elements (e.g. O, Ne, and Mg). Degenerate stars leading to Type Ia supernovae produce significant amounts of the Fe-peak elements (e.g. Cr, Mn, Fe, and Ni).

This thesis

First, I focus on updating the atomic data for radiative recombination in the SPEX code. Radiative recombination (RR) is a fundamental atomic process. I use the updated collisional ionizied and photoionized plasma models to better understand the physics of circumnuclear media in active galactic nuclei and the nitrogen enrichment in the the hot X-ray halos of ellipticals, groups, and clusters of galaxies.

1. Previously, the RR rate coefficients (i.e., the electron capture rates per ion) in SPEX were approximated with a power law. In **Chapter 2**, I propose a slightly more complicated mathematical function, which matches much better ($\lesssim 5\%$) the state-of-the-art RR rate coefficients.

2. In **Chapter 3**, I update the AUTOSTRUCTURE and ADASRR codes to systematically calculate detailed electron energy loss rates due to radiative recombination. This is the first time the electron energy loss rates due to RR of He-like to Ne-like ions have been calculated.

3. A theoretical study of density diagnostics using absorption lines from metastable levels is presented in **Chapter 4**. With the self-consistent PhotoIONization (PION) model in the SPEX code, we are able to calculate detailed level populations, including the ground and metastable levels. This enables us to determine under what physical conditions the metastable levels are significantly populated. I also reanalyze high-resolution grating spectra of NGC 5548 observed with Chandra in January 2002 using a set of PION components for the photoionized outflow. We derive lower (or upper) limits of plasma density in five out of six PION components based on the presence (or absence) of the metastable absorption lines.

4. The X-ray narrow emission features in the archetypal Seyfert 1 galaxy NGC 5548 are studied in **Chapter 5**. I provide the alternative interpretation that the X-ray narrow emission features in NGC 5548 can be described by a two-phase photoionized plasma with different ionization parameters and kinematics, and no further absorption by the warm absorber components. Moreover, I find that the X-ray and optical narrow emission line regions are most likely the same multi-phase photoionized plasma. The X-ray narrow emission line region is not the counterpart of the UV/X-ray absorber outside the line of sight because their distances and kinematics are not consistent.

5. In **Chapter 6**, I focus on the broad X-ray emission features in another Seyfert 1 galaxy, NGC 3783. I compare the December 2016 RGS spectra to the time-averaged RGS spectrum obtained in 2000–2001. The continuum was obscured in December 2016 but not in 2000–2001. We find a statistically significant broad emission component in the time-averaged RGS spectrum in 2000–2001. This X-ray broad emission component seems to be significantly weaker in December 2016. I demonstrate that the apparent weakening might be due to the extra screening by the obscurer, indicating that the obscurer is located further than the X-ray broad-line region.

6. In **Chapter 7**, I investigate the nitrogen enrichment in the chemical evolution RGS sample. For a standard initial mass function, low- and intermediate-mass stars are the main metal factory of nitrogen in the hot X-ray halos of ellipticals, groups, and clusters of galaxies. I also point out that the abundances of odd-Z elements (e.g. N, Na, Al, and Mn) are sensitive to the initial metallicity of the progenitors but they are not well constrained with current instruments (**Chapter 7**). Nonetheless, future missions like *XARM* with sufficient spectral resolution and photon collection area are required to put tight constraints on the abundances of odd-Z elements so that we can break the degeneracy on initial metallicity of the progenitors.