Abstract

At various levels of the cosmic hierarchy, the mass, energy, and angular momentum are redistributed through multiple astrophysical processes. One of the agents for such redistribution is the accreting compact objects, such as black holes and neutron stars in binaries. They accumulate matter through accretion from the surrounding environment and emit some fraction of it via jets and outflows. They are called "X-ray binaries" and ∼150 of them are known in our Galaxy. X-ray spectroscopy is a unique observational tool to unveil their redistribution processes. The goal of this thesis is to demonstrate that 3D radiative transfer modeling is a requisite to interpret the observed X-ray spectra. We apply the models based on the radiative transfer to the observed data of an actual object, show the effectiveness and limitations of the modeling, and demonstrate that this is the way to go in the X-ray microcalorimeter spectroscopy, which has just begun by the launch of *XRISM*.

We chose Circinus X-1 (Cir X-1 hereafter) as the target of this study. Amongst all the X-ray binaries, Cir X-1 stands out as an exception. None of the known X-ray binaries exhibit all the features observed in Cir X-1; (i) X-ray flux and spectral variability at various time scales, (ii) association to a radio jet and a supernova remnant (SNR) that gave birth to the neutron star, (iii) X-ray P Cygni line profile, which is a direct evidence of precense the outflowing material. The association with an SNR and a rapid decay of the 16.7 day orbital period suggest an extremely young age of ∼5000 years, making it the youngest known X-ray binary, hence an active agent of the mass, energy, and angular momentum redistribution. Cir X-1 is also a mysterious source. Despite observations over half a century, it is not even classified as a low-mass or high-mass X-ray binary. The binary inclination is unknown either. The origin of the X-ray continuum emission and significant variability associated with the orbital phase are also unknown.

We conducted the X-ray observations of Cir X-1 using *NICER* to cover an entire 16.7 day orbit. For the first time, the X-ray spectra of a uniform quality capable of resolving major emission lines were obtained at the highest cadence; at least once every four hours, corresponding to four degrees in azimuthal resolution in the viewing direction. Such a data set was not available before the advent of *NICER* in 2017, which features in a large collecting area with focusing optics, moderate energy resolution, and operational flexibility. The observed spectra exhibit a variety of appearances based on which the three (dip, flaring, and stable) phases were defined. Although the spectral appearances are very different, we successfully constructed a common spectral model that explains all three phases consistently with varying parameters. The model consists of partially covered disk blackbody emission plus H-/He-like Mg, Si, and S emission lines stemming from the photoionized plasma. The emission lines, in particular those of Fe, sometimes switch to the absorption lines.

Based on the phenomenological spectral model, we constructed a 3D geometry model of the binary system. The geometry includes the neutron star and the accretion disk at the center, which provides the incident X-ray emission for the photoionized plasma responsible for the line emission. The accretion stream from the companion star generates a geometrically-flared structure at a certain azimuth at the outer edge of the accretion disk, which makes the dip in the X-ray flux. The tail of the accretion stream is fragmentary, which causes rapid changes in the X-ray flux in the flaring phase after the dip phase. The emission lines suffer from little absorption due to the circumstellar matter even when the incident continuum emission is significantly absorbed, and the ionization

degree derived from the H/He-like line pairs is relatively stable over the entire orbit. This strongly suggests that the photoionized plasma responsible for the emission/absorption lines is located outside of the accretion disk.

Based on the 3D geometry model, we further proceeded to 3D radiative transfer modeling using the three different numerical solvers, `XSTAR`, `SKIRT`, and `MONACO`. We picked up three remarkable observational features to be explained by the radiative transfer model: (1) change between the emission and absorption lines, (2) P Cygni profile of the Fe XXV and XXVI lines, and (3) Continuum X-ray flux changes in an orbit. We synthesized the X-ray spectra separately for the transmitted, scattered, and diffuse components. By considering a velocity structure and 3D distribution of the partial covering material, all three observed features are qualitatively reproduced, demonstrating the effectiveness of the 3D radiative transfer modeling. Based on these findings, we argue some unsettled disputes about this mysterious source.