Ionized winds driven away from black holes (SPEX/PION thread)

Junjie Mao*

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1 Context

Ionized winds driven away from black holes across different mass scales have been observed with X-ray and UV grating instruments (e.g., HST/COS, XMM-Newton/RGS, Chandra/HETGS, and Chandra/LETGS) over the past two decades. We still have quite some gaps in our understanding of these ionized winds, such as their origin, structure, and impact on the evolution of black holes, circumnuclear media, and host galaxies.

*Department of Astronomy, Tsinghua University

2 Overview

In this thread, we will use the *pion* (photoionization equilibrium plasma) model in SPEX to measure the physical properties (e.g., hydrogen column density, ionization parameter, wind velocity) of the ionized winds.

For teaching and learning, we use a simulated Chandra ACIS-S/MEG 1st-order spectrum (exposure: 100 ks). We also use the old atomic data ("var calc old" in SPEX, default) for fast calculations. When dealing with real observed data, one should use the new atomic data "var calc new" in SPEX). You can learn more about the setting here.

Notice: To maximize the learning outcomes, follow this thread step-by-step. All the assignments (in blue) should be completed in a scientific writing report with proper text, tables, and figures.

3 Preparation

Install SPEX and download all the files in the cloud drive

- Spectral data files bhiw_amo1.spo and inst_amo1.res

4 Target bio

Our target black hole is called PG J2024-0820 at a cosmological redshift of 0.01158. The line of sight Galactic hydrogen column density is 8.5×10^{21} cm^{-2}.

5 Step-by-step guide

Hint: The log command in SPEX can be quite useful throughout the entire exercise.

5.1 Read and plot the spectrum

Read the data into SPEX and plot the spectrum in the wavelength-flux space (Å for the X-axis and Counts s^{-1} m^{-2} Å^{-1} for the Y-axis). You can also plot the spectrum in the energy-flux space (keV for the X-axis and Counts s^{-1} m^{-2} keV^{-1} for the Y-axis). The documentation of these SPEX commands might be useful: data, ignore, obtin, plot and the plotting reference.

Question: What are the disadvantages of plotting the spectrum in units of Counts s^{-1} Å^{-1} or Counts s^{-1} keV^{-1}?

5.2 Model set-up

Several groups of spectral models are typically required to analyze ionized winds running away from black holes. The first two model components are cosmological redshift (*reds*) and Galactic absorption (*hot*). Both these two models are multiplicative models. Don't forget to use the *par* command to set the redshift value and Galactic hydrogen column density properly.

5.2.1 Continuum

Then, we need to set up the continuum model components. Ignoring the data above 5 Å (i.e., $\lesssim 2.5$ keV) and plot the spectrum again. We found that the continuum follows a power-law shape. Therefore, we add a power-law component (*pow*), which is an additive model. Using the *comp* command to set the relationships among the (additive and multiplicative) model components properly, i.e.

$$hot \times reds \times pow \tag{1}$$

To check the set-up of model components and relations, one can use the command "model show".

Fit the hard X-ray data with the power-law model. Tip: A reasonable guess is often necessary for the fitting. This can be achieved by varying the parameter values, *calc* and *plot* a few times. The initial attempts of the normalization might be rather large or small, hence, plotting the Y-axis in the log scale with a wide range might be necessary to find the model prediction.

While the power-law continuum fits the hard X-ray data well, the soft X-ray data is well above the power-law continuum. This can be seen clearly by re-using the soft X-ray data (Tip: one needs to re-bin the soft X-ray data again). Accordingly, another continuum model component is required. Here, we add a modified black body (*mbb*) component to the continuum model,

$$hot \times reds \times (mbb + pow) \tag{2}$$

Apparently, *mbb* is an additive model.

Fit the broad (soft and hard) X-ray data with the $mbb + pow$ continuum model.

5.2.2 Explore the Galactic absorption model

In the step above (Sct. 5.2.1), you might wonder if you can switch the order of *hot* and *reds*? Let's explore the Galactic absorption model by plotting the model (Eq. 1) spectra ("plot type model" in SPEX) in the wavelength-flux space. Tip: Set "plot fill disp false" to see the absorption line features.

List the top three absorption lines (incl., wavelength). Tip: A spreadsheet (online or not) might be particularly useful for many reasons.

Zoom in to the $6-8$ Å wavelength range where a prominent absorption line can be found. Use the *par* command to reset the value of the redshift component (*reds*) to 0.1 temporarily and switch the order of the two multiplicative models in Eq. 1. Tip: The set up is only effective after the "calc" command.

Question: How to interpret the difference between the two sets of component relations? Hint: What is the wavelength difference before and after switching the order? What is the relation to the temporary redshift value?

Let's reset the *reds* value to 0.01158 and further explore the Galactic absorption model.

Plot and compare the absorbed power-law model spectra in the wavelength-flux space (1) with different Galactic column densities ($N_{\rm H} = 10^{19},\ 10^{20},\ 10^{21}, ..., \ 10^{24}\ {\rm cm}^{-2}$); (2) with $N_{\rm H} = 10^{22}\ {\rm cm}^{-2}$ (frozen) but different temperatures ($t = 10^{-3},\ 10^{-2},\ 10^{-1},\ 1,\ 10,\ 100$ eV). Summarize the trends of the absorption feature with increasing $N_{\rm H}$ or t. Tip: Use the "plot adum ... " command to dump the plot data to an ascii file. Use python or similar to show multiple absorbed power-law spectra in one figure. .

While the redshift component (*reds*) has been set up so far, the target distance has not been set via the *dist* command (the default distance in SPEX is 10^{22} m). Once the distance is set properly, the flux and luminosity in a given energy band are meaningful (to change the energy band, one can use the *elim* command).

Question: How did the $0.5 - 10$ keV flux and luminosity change before and after setting the distance properly? Calculate the flux and luminosity relation, does it follow the inverse distance-square relation exactly? If not, why?

5.2.3 Explore the PION absorption model

After considering the continuum model and Galactic absorption, the model is still far from satisfactory. Now, let's introduce the photoionization equilibrium plasma model – *pion*. Add one *pion* (multiplicative) component and set the component relation properly.

$$hot \times reds \times pion \times (mbb + pow) \tag{3}$$

Tip: If you doubt if order matters, try similar exercises as Sct. 5.2.2.

Before fitting *pion* as a black box, we should first explore the *pion* model. Again, plot the model spectra (Eq. 3) in the wavelength-flux space.

Plot and compare the model spectra (1) with different *pion* column densities ($N_{\rm H} = 10^{19},\ 10^{20},\ 10^{21}...,\ 10^{24}\ {\rm cm}^{-2}$); .

Tip: Use the "plot adum ... " command to dump the plot data to an ascii file. Use python or similar to show multiple absorbed power-law spectra in one figure. .

To be continued below