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

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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.

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## 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 is called MG J2024-0820 at the cosmological redshift of 0.01158. The line of sight Galactic hydrogen column density is $8.5 \times 10^{21}$ 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 Continuum model set-up

Next, 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 spectrum with the model set up as Eq. 2.

### 5.3 Explore the Galactic absorption model

In the step above (Sct. 5.2), 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 ($N_{\rm H} = 10^{19}$, $10^{20}$, $10^{21}$, ..., $10^{24}$ cm$^{-2}$); (2) with $N_{\rm H} = 10^{22}$ 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. .

1. mbb component also have t, so it may lead to misunderstanding.
2. There is a redundant dot at the end of the paragraph.

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?

### 5.4 Intrinsic Spectral Energy Distribution (SED)

In the step above (Sct. 5.2), we have set up a simple SED consisting of a modified black body and a power law. Ionizing SED is critical for any photoionized plasma, including the black hole winds here. It is necessary to examine the SED before continuing.

Intrinsic SED is the one that comes from the central engine (including the hot corona, accretion disk, and so forth). This is also the SED seen by the photoionized plasma closet to the central engine. Apparently, the Galactic absorption effect caused by the *hot* component should not be included in this subsection. Tip: There are two methods to ignore the Galactic absorption effect. One is to use the comp command, and the other is to use the par command.

Plot the intrinsic SED model in the energy-flux space. Set the X-axis to 0.1 eV$-10^4$ keV and Y-axis units to W m$^2$. Describe the intrinsic SED in the infrared, optical, and gamma-ray bands. Tip: Refer to this page for setting up the units properly..

While both the *mbb* and *pow* components are constrained by the observed (to be more precise, simulated) data, both models extend beyond the X-ray band. When we have multi-wavelength data to constrain the broad-band SED, we certainly want to limit the range of the continuum model constrained by the X-ray data. For *mbb*, UV data might require a different model (e.g., *comt*). For *pow*, one might take advantage of the *etau* model to add exponential cut-off to both the low- and high-energy ends.

Use two *etau* models to exponetially cut-off the *pow* continuum below 1 Rydberg and $10^3$ Rydberg. Plot and compare the intrinsic SED models in the energy-flux space before and after the cut-off. Set the X-axis to 0.1 eV $-$ $10^4$ keV and Y-axis units to W m$^2$.

### 5.5 Explore the PION absorption model

After considering the continuum model and Galactic absorption, the model is still far from satisfactory (as one can see after switching back to "plot type data"). To fit the numerous absorption features, we need to use the photoionization equilibrium plasma model – *pion*. Add one *pion* (multiplicative) component and set the component relation properly.

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

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 ($N_{\rm H}$ = $10^{19}$, $10^{20}$, $10^{21}$..., $10^{24}$ cm$^{-2}$); (2) with $N_{\rm H} = 10^{22}$ cm$^{-2}$ (frozen) but different $\log \xi$ = 0, 1, 2, ..., 4, 5, where ionization parameter $\xi$ is in units of erg s$^{-1}$ cm (i.e., $10^9$ W m). Summarize the trends of the absorption feature with increasing $N_{\rm H}$ or $\log \xi$.

According to the above knowledge, guess a suitable combination of $N_{\rm H}$ or $\log \xi$. Tip: To reproduce the Fe UTA (Unresolved Transition Array) feature, what is the approximate ionization parameter? It might be necessary to adjust the continuum parameters as well.

Fit the spectrum with the model set up as Eq. 3.

While the Fe UTA feature might be well fitted, there are more absorption features in the spectrum not well represented by the best-fit model so far. Apparently, we should try adding another *pion* component:

$$hot \times reds \times pion_1 \times pion_2 \times (mbb + pow) \tag{4}$$

Starting with a reasonable guess, fit the spectrum with the model set up as Eq. 4. Write a discussion section on the suitable order of the two *pion* components.

Since we are dealing with a high-resolution X-ray spectrum, it is necessary to look at details (e.g., a narrow wavelength/energy range). Plot only the $11.7 - 12.3$ Å wavelength range, and try to adjust the line width and broadening of the *pion* components. Tip: Keep in mind that zoom-in is necessary for high-resolution X-ray spectrum!

Make a list of the absorption lines in this wavelength range. Which *pion* component gives rise to which absorption line?

Starting with a reasonable guess, fit the spectrum with the model set up as Eq. 4 again. This shall lead you to the final best-fit parameters.