HUT Observations of Time-Variable Absorption in NGC 4151

Department of Physics and Astronomy, and Center for Astrophysical Sciences, Johns Hopkins University, Baltimore MD 21218

Abstract. We present the results of ultraviolet spectral monitoring of the Seyfert galaxy NGC 4151 performed by the Hopkins Ultraviolet Telescope during the Astro-2 mission. We show how the response of the Lyman continuum optical depth to variations in the continuum flux may be used to derive estimates of the distance of the absorbing gas from the central object. In this case, it seems that the absorbing gas is located \( \leq 50 \text{ pc} \) away from the central source.

1. Introduction

Most work analyzing the absorption lines that tell us about AGN outflows is done on single observations. We then study the detailed shapes of the line profiles to infer the character of the gas as a function of line-of-sight velocity. As is evident by a comparison of the different models discussed at this meeting, it is very difficult to attach a radial scale to these inferences.

Time-variability offers a valuable new perspective, particularly when the ionization state of the absorbing gas is controlled by photoionization due to the AGN continuum. Unlike the case of variability in emission lines, there is no ambiguity about whether the photoionized gas sees a different continuum than the one we do—the continuum directed at the gas is the same continuum shining at us, and there is identically zero time delay between the luminosity we see now and the luminosity incident upon the gas when it did the absorbing. For these reasons, the interpretation of time-variable absorption lines is far more direct than the interpretation of time-variable emission lines.

2. Observations

To pursue this program (and for several other reasons), we observed the bright type 1 Seyfert galaxy NGC 4151 with the Hopkins Ultraviolet Telescope (HUT) six times over a span of 11 days during the Astro-2 mission of February/March, 1995. To show the quality of the data we obtained, we first present a spectrum based on a sum of all our data (Figure 1, from Kriss et al. 1995). As can be easily seen, the signal/noise ratio of these data are high enough to permit the identification of large numbers of lines, both in absorption and in emission, including some that are quite weak. The absorption lines seen span a wide range in ionization, from \( \text{O}^{+5} \) and \( \text{N}^{+4} \) to \( \text{C}^{+1}, \text{Si}^{+1}, \text{and Fe}^{+1} \). What is not so easily seen in this figure is that there is definite Lyman continuum absorption at a
redshift of $320 \pm 60\,\text{km}\,\text{s}^{-1}$; that is, blueshifted by $\simeq 700\,\text{km}\,\text{s}^{-1}$) from the systemic redshift of NGC 4151.

The luminosity of NGC 4151 varied substantially over the course of these observations. If we take as a fiducial continuum level the flux at 1450Å, we saw the flux rise from $\simeq 4.5 \times 10^{-13}\,\text{erg\,cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$ on 4 March to almost double that ($\simeq 8 \times 10^{-13}\,\text{erg\,cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$) on 7 March, and then watched it drop back down to a level only slightly higher than at the beginning of this experiment.

A particularly noteworthy feature of the spectral time-variability was the change in Lyman edge optical depth. This is best seen in a sequence of normalized spectra (Figure 2), in which each day’s spectrum is displayed as a ratio to the mean spectrum. While the shape of the continuum and the equivalent widths of both the emission and the absorption lines changed very little, the relative flux in the Lyman continuum clearly swings sharply up and down.

The drop in flux at the redshifted Lyman edge is easily translatable into a column density of neutral hydrogen atoms. The variations in this column density vis-a-vis the variations in the continuum flux are shown in Figure 3. The sharp rise in the continuum near the beginning of the observations is mirrored by an equally sharp fall in the HI column density, while the slow decline in the continuum power towards the end of the observations is reflected in a slow, and delayed, recovery in the HI column. At least at the qualitative level, such behavior is exactly what one would expect from gas whose neutral fraction is regulated by exposure to the central engine’s ionizing continuum.
3. Ionization Analysis

We can investigate this relationship more quantitatively by examining the detailed relationship between the time-variation of the neutral H density and the ionizing continuum:

\[
\frac{dn_{HI}}{dt} = n_e n_p \alpha_{rec} - n_{HI} \int \frac{L_\nu}{4\pi r^2 h\nu} \sigma_{ion}(\nu),
\]

where \(n_e, n_p\) are the electron and proton densities, \(\alpha_{rec}\) is the radiative recombination coefficient, \(\nu_H\) is the frequency of the Lyman edge, \(L_\nu\) is the luminosity per unit frequency in the continuum, \(r\) is the distance of the absorbing gas from the source of radiation, and \(\sigma_{ion}\) is the photoelectric cross section.

It is convenient to divide through equation 1 by \(n_{HI}\), to yield

\[
\frac{d \ln n_{HI}}{dt} = n_e \alpha_{rec} \Phi^{-1} - F_{ion} \frac{1}{h\nu_H} \langle \sigma_{ion} \rangle,
\]

where \(F_{ion}\) is the integrated ionizing flux at the location of the gas, \(\langle \sigma_{ion} \rangle\) is the photoelectric cross section appropriately averaged over the ionizing spectrum, and \(\Phi = n_{HI}/n_p\). When the equation for the rate of change of the neutral density is written in this form, it is apparent that the timescale for change of the column density \(t_s\) is simply

\[
t_s^{-1} = t_{rec}^{-1} - t_{ion}^{-1},
\]

where the recombination timescale is

\[
t_{rec} = \frac{\Phi}{n_e \alpha_{rec}}
\]
and the ionization timescale is

$$t_{ion} = \frac{h \nu_H}{F_{ion}(\sigma_{ion})}.$$  \hfill (5)

In equilibrium, the ionization and recombination timescales are equal. When the gas is out of equilibrium in the sense that ionization dominates recombination (that is, the gas is less ionized than it would be at the current flux level), $t_s \geq t_{ion}$. In the limit that ionization completely dominates recombination, $t_s \to t_{ion}$. Since $t_s$ depends only on the ionizing flux at the location of the absorbing gas, and we measure the ionizing flux at Earth, in this situation $t_s$ may be used to estimate the distance of the absorbing gas from the central source:

$$r \leq \left(\frac{f_{ion}(\sigma_{ion})t_s}{h \nu_H}\right)^{1/2} D,$$  \hfill (6)

where $f_{ion}$ is the ionizing flux measured at Earth, and $D$ is the distance from the continuum source to Earth.

Inference of conditions in the absorber by using $t_s$ during periods of net recombination is a bit more indirect. As equation 4 shows, when $t_s \geq t_{rec}$, we are not (as is commonly supposed) given a direct estimate of $n_e$. Instead, we obtain an estimate of the ratio $n_e/\Phi$, where the ratio of neutrals to protons $\Phi$ is a priori unknown, and could be very different from unity. However, it is possible to derive a different quantity, the departure of the ionization balance
from equilibrium, when periods of both net recombination and net ionization are observed in the same object.

The argument begins with the instantaneous equilibrium neutral/ionized ratio

\[ \Phi_{\text{eq}}(t) = \frac{n_e \alpha_{\text{rec}} h \nu_H}{F_{\text{ion}}(t) \langle \sigma_{\text{ion}} \rangle}. \]  

(7)

We assume that \( n_e \) is constant on the timescale of the observed fluctuations. With this assumption, we may use equation 7 to write \( n_e \) in terms of \( \Phi_{\text{eq}}(t) \) and \( F_{\text{ion}}(t) \). Substituting this expression for \( n_e \) in the definition of \( t_{\text{rec}} \) gives

\[ t_{\text{rec}}(t) = \Phi(t) \frac{h \nu_H}{\Phi_{\text{eq}}(t) F_{\text{ion}}(t) \langle \sigma_{\text{ion}} \rangle}. \]  

(8)

Since we may estimate \( t_{\text{rec}} \) from \( t_\ast \) (in the same limiting sense as when we estimate \( t_{\text{ion}} \) from \( t_\ast \) during periods of net ionization), we find

\[ \frac{\Phi(t)}{\Phi_{\text{eq}}(t)} \leq \left( \frac{f_{\text{ion}}(t) t_\ast(t) \langle \sigma_{\text{ion}} \rangle}{h \nu_H} \right) \left( \frac{D^2}{r^2} \right). \]  

(9)

Now we apply these arguments to the changing neutral column density and ionizing flux we observed in NGC 4151. When the neutral column was falling, the timescale for a decrease by a factor of \( e \) was \( \simeq 2 \) d or less, and the observed ionizing flux density at the Lyman edge (after correction for Galactic extinction) was \( \simeq 9 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \). The distance from the ionizing source to the absorbing gas is then

\[ r \leq 50 \left( \frac{D}{15 \text{Mpc}} \right) \text{pc}. \]  

(10)

Note that this is an upper bound in two senses: in the sense we have already discussed, that recombination might partially cancel ionization; and, because we do not have arbitrarily fine time resolution, the real \( t_\ast \) might be less than our estimate of \( \simeq 2 \) d. On the other hand, when the neutral column rose, the \( e \)-folding timescale was more like 3 d, and the Lyman edge flux density was slightly smaller, \( \simeq 7 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \). Using the upper bound on \( r \) just found, the departure from equilibrium is

\[ \frac{\Phi}{\Phi_{\text{eq}}} \leq 1. \]  

(11)

On the one hand, this appears to be a tautological result—when the gas is recombining \( \Phi \) must be less than \( \Phi_{\text{eq}} \). On the other hand, since a significantly smaller \( r \) would lead to a larger value of \( \Phi/\Phi_{\text{eq}} \), we argue that the requirement of consistency suggests that 50 pc is not a tremendous overestimate. If so, the gas is also not too far from equilibrium, even during these column density fluctuations.

Acknowledgments. This work was partially supported by NASA Contract NAS 5-27000, and NASA LTSA Grants NAGW-3156 and NAGW-4443.
Discussion

Roger Blandford: Do you think that you can account for the variable absorption by moving the source—e.g., if it is a hot spot on an accretion disk?

Julian Krolik: I think that’s unlikely. Let’s make the approximation that the flux we see is dominated by the moving hot spot. Then the change in column density might be attributed to inhomogeneity in the absorber on the scale of the displacement in the hot spot. NGC 4151 has a bolometric luminosity $\sim 10^{44}$ erg s$^{-1}$. If it is accreting at 0.1 Eddington, its central black hole is $\sim 10^7 M_\odot$, so the brightest part of the accretion disk, at $\sim 10$ gravitational radii, would have a size $\sim 1$ AU. So in this picture, there would have to be order unity column density fluctuations in interstellar material on very small length scales. In addition, if the change in column density is due solely to such inhomogeneities, why does it change in the appropriate sense relative to the continuum flux?

Richard Mushotzky: Does lack of response of CIV, etc. strongly constrain the model?

Julian Krolik: It’s not a very strong constraint for several reasons. First, the CIV 1549 doublet, and many of the other strong lines, are clearly saturated, so that their equivalent widths are very insensitive to column density. Some of the other lines, such as SiIV 1400 are unsaturated (as judged by their multiplet ratios), and do vary somewhat. The SiIV line variations actually resemble the Lyman edge variations, but with somewhat smaller fractional amplitude. Second, the fact that we see a very wide range in ionization states, yet only modest Lyman edge optical depth, demonstrates that the ionization parameter (the ratio of ionizing intensity to gas density or pressure) varies considerably along the line of sight. So the highly-ionized gas containing the CIV (or SiIV or . . .) atoms may not be anywhere near the neutral H atoms. Finally, if most of the optical depth in the absorption lines is accumulated in regions where that ionization stage is the dominant one, changes in ionizing flux don’t change the ionization balance very much. H changes more because in most photoionized conditions $\Phi \ll 1$.

References

Kriss, G.A., Davidsen, A.F., Zheng, W., Kruk, J.W., and Espey, B.R. 1995, ApJ454, L7