The Chandra High Resolution Spectra of Mkn 421

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Abstract. Mkn 421 was observed by Chandra twice, on November 5, 1999 as part of the Chandra calibration program, with the ACIS-HETG configuration, and on May 29, 2000 following our Target Of Opportunity request aimed to catch the source in an ultra-high state, with both the ACIS-HETG and the HRC-LETG configurations. In this contribution we present and compare the two Chandra-MEG observations of Mkn 421, which lasted 26 and 19.6 ks respectively.

1. Introduction

Mkn 421 (cz = 9234 km s\(^{-1}\), Ulrich et al., 1975) is a low redshift blazar, intensively studied over all frequencies. Recent X-ray observations of this source during a monitoring campaign performed by Beppo-SAX have clearly shown that the beamed continuum emission from Mkn 421 undergoes spectral variability correlated with flux changes (Malizia et al., 2000, Fossati et al., 2000). These spectral changes are driven by the shift of the synchrotron peak emission towards higher energies as the source brightens. This causes a flattening of the 0.1-10 keV spectrum when the source is in its outburst phases.

In this paper we present the first, high-quality, Medium Energy Grating (MEG) high resolution spectra of Mkn 421, taken by Chandra with the ACIS-HETG configuration on November 1999 and May 2000. These two observations clearly confirm the findings of Malizia et al. (2000) and Fossati et al. (2000), showing a marked spectral variability of the nuclear continuum in between them. We also look for narrow absorption and emission features that could have escaped detection in the previous low-resolution X-ray spectra of this source. We present here the results of our analysis.
2. Data Reduction and Analysis

Mkn 421 was observed with the Chandra ACIS-HETG configuration twice, on November 5, 1999 (as a calibration target) and on May 29, 2000, following a DDT (Director’s Discretionary Time) aimed to catch the source in a very high intensity state. Both sets of data were processed, and then reduced, with the latest version of the Chandra Interactive Analysis of Observations software (CIAO2.0, Elvis, 2001, in preparation), using the most updated calibrations. Standard grade filtering was applied to order-sorted event-2 files (ASCA grades 0, 2, 3, 4, 6). Spurious events accumulated on streaks along the read-out axis of the CCD chips during single read-out phases were removed using the Chandra contributed tool destreak (Houck J.1).

First to third order source and background MEG spectra for both the observations were extracted from the order-sorted and cleaned event-2 files using the tool tgeextract in CIAO2.0. For each order we rebinned the counts-per-bin histograms by given factors, added positive and negative orders, subtracted the background from the source spectrum, and divided by the effective area, the exposure time and the width of the bins in Å, to end up with binned “fluxed” spectra in units of ph s⁻¹ cm⁻² Å⁻¹.

In the following we present the spectral analysis of the MEG first order spectra. The compared analysis of all the HETG/LETG data is deferred to a forthcoming paper (Nicastro et al., 2001a, in preparation).

3. Spectral Analysis

3.1. The Nuclear Continuum and Its Wavelength-Dependent Variability

During the 2000 May Chandra-MEG observation (hereinafter MEG00), Mkn 421 was more than one order of magnitude brighter than during the previous 1999 November observation (MEG99), in the entire 2-26 Å band. However these changes were wavelength-dependent, as shown, in a model-independent way, in Figure 1, where we plot the ratio between the MEG00 and MEG99 spectra. This ratio clearly shows that the source brightened by almost an order of magnitude in the soft band (above ~ 12 Å) and by much large factors in the hard band (λ<12Å), so flattening considerably between the two observations. We note that most of the spikes present in this ratio correspond to 1-bin negative fluctuations in the very noise MEG99 spectrum (but see also next section).

Detailed fitting confirms the spectral variability shown by the ratio in Figure 1. We fitted simultaneously the fluxed MEG spectra of Mkn 421 in Sherpa, using a model consisting of a power law attenuated by interstellar absorption (whose hydrogen equivalent column density was constrained to be larger than the Galactic column along the line of sight: \(N_H = 1.45 \times 10^{20}\) cm⁻², Elvis, Lockman & Wilkes, 1989). All the parameters were left free to vary independently between the two sets of data. The result of this fit is shown in Table 1 (where power law parameters have been converted into energy-fluxed spectra, in units of ph

http://asc.harvard.edu/ciao/download_scripts.html
Figure 1. Ratio between the MEG spectra of Mkn 421 taken during the two Chandra observations of 1999 November and the 2000 May.

\( \frac{\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}, \text{at 1 keV}}{\text{}} \). Reported errors are at a 2-\( \sigma \) level for 1 interesting parameter. During both the observations the amount of neutral absorption is consistent with the Galactic one. The 0.5-6 keV beamed continuum of Mkn 421 flattened by \( \Delta \Gamma = 0.64^{+0.18}_{-0.07} \) between the two observations, while brightening by a factor of \( \sim 19 \).

### 3.2. High Resolution Spectral Analysis

The presence of ionized gas in the blazar environment or along the line of sight, between us and the source, can be efficiently investigated at high spectral resolution, looking for narrow absorption and/or emission features in the soft X-ray band. In particular OVII and OVIII ions can imprint strong K\( \alpha \) and K\( \beta \) resonant (R) absorption lines at 21.602 (OVII K\( \alpha \)), 18.63 (OVII K\( \beta \)) and 18.97 Å (OVIII K\( \alpha \)) (rest frame), while strong intercombination (I) and forbidden (F) OVII K\( \alpha \) emission is expected at 21.9 and 22.1 Å respectively. In Figure 2 we show the 18-24 Å portion of the MEG99 (upper panel) and MEG00 (lower panel) spectra of Mkn 421, along with their best fitting models (red curves). The spectra are binned by a factor of 10, which corresponds to a bin-width of \( \Delta \lambda = 0.05 \) Å (i.e. \( R = 400 \) at 20 Å). No clear absorption or emission line is visible in the MEG00 spectrum. However, the MEG99 spectrum shows both negative and positive deviations from the best fitting continuum model that involve several adjacent bins and so are likely to be true, relatively broad, emission and absorption lines. We then tried to fit the most significant (\( \sim 2\sigma \) per bin) of these features with single.

| Date     | \( ^a N_H \) | \( \Gamma \) | \( ^b \text{Norm} \) | \( ^c (0.5-6 \text{ keV}) \text{ Flux} \) |
|----------|--------------|-------------|----------------|--------------------------------|
| 11 Nov 99 | 1.40^{+0.14}_{-0.04} | 2.83^{+0.14}_{-0.05} | 5.8^{+0.2}_{-0.2} | 1.6 |
| 29 May 00 | 1.40^{+0.08}_{-0.0} | 2.19 ± 0.01 | 93.8 ± 0.6 | 33 |

\( ^a \text{In } 10^{20} \text{ cm}^{-2}. \quad ^b \text{In } 10^{-3} \text{ ph cm}^2 \text{ s}^{-1} \text{ keV}^{-1}, \text{at 1 keV.} \quad ^c \text{In } 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}. \)
positive and/or negative gaussians, with all parameters (i.e. normalization, position of the center and full width half maximum) free to vary. We fitted up to four gaussians to this portion of the spectrum, three in absorption, and one in emission, and tentatively identified two different absorbing/emitting systems of ionized gas with oxygen mostly distributed between OVII and OIX species. The lines identification is based on their relative positions, and we identify a system if more than one line from different atomic transitions is detected. None of these two systems is seen in the MEG00 spectrum of Mkn 421 (Fig. 2, lower panel), implying variability of the physical conditions of the reprocessing material, and so strongly suggesting its close association with the AGN environment. At the redshift of Mkn 421 (cz = 9234 km s\(^{-1}\), Ulrich M.H. et al., 1975, ApJ, 198, 261) the resonant OVII K\(\alpha\) falls at 22.267 \(\AA\). For our two systems we measure, \(\lambda_1(OVIIK\alpha) = 21.806 \ \text{\AA}\) and \(\lambda_2(OVIIK\alpha) = 20.153 \ \text{\AA}\). If these identification are correct, then the two absorbing/emitting systems are outflowing from the central source with velocities of \(v_{out}^1 = 6600\), and \(v_{out}^2 = 28500\) km s\(^{-1}\) respectively, maybe preceeding the jet along our line of sight. If this is the case, the disappearing of these systems during the outburst phase of Mkn 421 can be self-consistently accounted for by a sharp increase of the ionization degree of the gas due to photoionization by the beamed continuum emission.

Figure 2. 18-24 ÅMEG99 (upper panel) and MEG00 (lower panel) spectra of Mkn 421.
3.3. Searching for the WIGM

High resolution HST-GHRS observations of Mkn 421 show at least three strong absorption lines between 1220 and 1260 Å (Penton, Shull & Stocke, 2000, Penton, Stocke & Shull, 2000). One of these lines is identified as H Lyα absorption produced by an intervening intergalactic system at a redshift of \(cz = 3035 \pm 6\) km s\(^{-1}\), close to three galaxies at gas-to-galaxy distances of 2.14, 3.98 and 4.119 h\(^{-1}\) Mpc. The Doppler parameter associated to this line is \(b = 35 \pm 5\) km s\(^{-1}\), and, if the broadening is due only to thermal motion of the protons in the gas, it corresponds to a gas temperature of \(T = (1.4 \pm 0.4) \times 10^5\) K, and so to mildly ionized gas in thermal equilibrium. This Warm phase of the Intergalactic Medium (WIGM) is predicted by hydrodynamical simulation for the formation of the large-scale structures in the Universe (e.g. Hellsten et al., 1998; Cen & Ostriker 1999, Dave et al., 2000), and it is thought to host the majority of the baryonic matter in the local Universe (\(z < \sim 1\)). However, due to the lack of adequate resolution and high-contrast spectra in the soft X-ray regime, this fundamental baryonic component of the Universe, has so far escaped identification.

The Doppler parameter for oxygen ions in the intervening system along the line of sight to Mkn 421, is 4 times smaller than that measured for hydrogen, so suggesting full width half maxima of putative oxygen lines of the order of 10 km s\(^{-1}\). These are far narrower than the resolution of the MEG99 and MEG00 spectra plotted in Fig. 2, and so, ionized-oxygen absorption associated with this intervening system may well have escaped detection at those resolution. To detect such a WIGM cloud, a resolution of \(R \geq 1000\) is needed. The full resolution of the MEG at 20 Å is of \(R \sim 1000\), and an ungrouped MEG spectrum has a bin-width of 0.005 Å (i.e. \(\sim 70\) km s\(^{-1}\) at 22 Å), which then allows for 4 non-independent channels for resolution element. At these resolution the strongest lines from the WIGM can begin to show-up in spectra with adequate signal to noise ratio in the continuum (Nicastro et al., 2001b, in preparation). The full resolution MEG00 spectrum of Mkn 421 has \(\sim 10 - 15\) counts in the continuum at \(\sim 20\) Å, and so can be used to investigate the presence of such features.

Based on the observed properties of the UV Lyα system, we ran our resonant absorption models (Nicastro, Fiore and Matt, 1999) for a cloud of collisionally ionized gas with a temperature of \(T = 1.4 \times 10^5\) K, to predict what lines we should expect in the MEG00 spectrum of Mkn 421, and at which sensitivity level. We included the photoionization contribution by the diffuse EUV-to-X-ray background at the redshift of the intervening Lyα system of Mkn 421 (Nicastro et al., 2001b). The relative contribution of photoionization depends, of course, on the baryonic density in the cloud. At the redshift of this cloud the photoionization contribution becomes important for \(n_b \approx 10^{-5}\) cm\(^{-3}\). At higher density the dominating mechanism is collisional ionization and the gas is only mildly ionized with oxygen distributed between OIV and OVI. At these densities no line is expected to show up in high resolution X-ray spectra. For gas density of \(n_b \approx 10^{-6}\) cm\(^{-3}\), OVII has its maximum, and strong OVII Kα and Kβ are expected at \(\lambda = 21.821\) Å and \(\lambda = 18.819\) Å. Finally for densities lower than \(n_b \approx 10^{-7}\) photoionization dominates and the gas is almost fully ionized, with the oxygen mainly in its OVID-OIX stages. In this case resonant OVID Kα at \(19.162\) Å is predicted.
We then examined the full resolution MEG00 spectrum looking for these features. We did not find any significant absorption line at the expected wavelengths, and put the following $1 - \sigma$ upper limits on the observed equivalent widths: $\text{EW(OVII}\alpha) > -15 \text{ m} \text{Å}$, $\text{EW(OVII}\beta) > -3 \text{ m} \text{Å}$, and $\text{EW(OVIII}\alpha) > -3 \text{ m} \text{Å}$. These are still compatible with a WIGM filament with typical metallicities of $Z = 0.01 - 0.1Z_\odot$, equivalent hydrogen column densities of $N_H = 10^{18} - 10^{20} \text{ cm}^{-2}$, and densities lower than $10^{-5} \text{ cm}^{-3}$. Higher signal to noise observations are then needed to definitively address this important issue and constrain the volume and column densities of the local Ly$\alpha$ filament along the line of sight to Mkn 421, which in turn would allow one to estimate the baryonic mass contained in this filament.

4. Summary

In this paper we presented the first high resolution X-ray spectra of Mkn 421, taken with the Chandra-HETG on November 5, 1999 and May 29, 2000. The main results of our analysis can be summarized as follows: (a) the 0.5-6 keV continuum of Mkn 421 flattened by $\Delta \Gamma = 0.64^{+0.18}_{-0.07}$ between the two Chandra observations, while brightening by a factor of $\sim 19$. (b) Two absorbing/emitting systems of highly ionized gas have been tentatively identified in the low-state MEG spectrum of Mkn 421 through the detection of absorption and emission K$\alpha$ lines from OVII and OVIII ions. These two systems are not seen in the high-state spectrum of Mkn 421, so suggesting that they were intrinsic to the nuclear environment and became fully ionized, and so transparent, as the source brightened. If this interpretation is correct, the two systems were both outflowing from the central source with velocities of 6600 and 28500 km s$^{-1}$, maybe preceeding the jet along our line of sight. (c) Finally we demonstrated that both very high spectral resolution and high signal to noise data are required to detect high-ionization absorption lines from the WIGM, and used the high signal to noise MEG spectrum of Mkn 421 at full resolution to put limits on the equivalent widths of the predicted OVII and OVIII K$\alpha$ and K$\beta$ resonance absorption lines that are likely to be associated to the intervening H Ly$\alpha$ system along the line of sight to this source.

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