A SUZAKU X-RAY STUDY OF THE PARTICLE ACCELERATION PROCESSES IN THE RELATIVISTIC JET OF BLAZAR Mrk 421

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ABSTRACT

We report on the findings of a 364 ks observation of the BL Lac object Mrk 421 with the X-ray observatory Suzaku. The analysis in this paper uses fluxes and hardness ratios (HRs) in the broad energy range from 0.5 keV to 30 keV. During the course of the observation, the 0.5–30 keV flux decreased by a factor of ~2 and was accompanied by several large flares occurring on timescales of a few hours. We find that fitting a broken power model to spectra from isolated epochs during the observation describes the data well. Different flares exhibit different spectral and HR evolutions. The cumulative observational evidence indicates that the particle acceleration mechanism in the Mrk 421 jet produces electron energy distributions with a modest range of spectral indices and maximum energies. We argue that the short-timescale X-ray spectral variability in the flares can be attributed mostly to intrinsic changes in the acceleration process, dominating other influences such as fluctuations in the Doppler beaming factor, or radiative cooling in or outside the acceleration zone.

Key words: acceleration of particles – BL Lacertae objects: individual (Mrk 421) – galaxies: jets – X-rays: galaxies

1. INTRODUCTION

TeV blazars exhibit $\nu F_\nu$ spectral energy distributions (SEDs) with two broad peaks: one in soft to medium X-rays and the other at GeV energies. The amplitude and the position of the peak change with time, sometimes in a correlated way (e.g., Blazejowski et al. 2005). The emission is highly polarized in radio through optical wavelengths (e.g., Piner & Edwards 2005; Homan et al. 2000; Lister & Smith 2000). The radio through X-ray spectrum is thought to be the result of synchrotron emission from the highest energy electrons and positrons accelerated to Lorentz values $\gamma > 10^3$ by shock fronts in the jet. Inverse Compton scattering from the same population of electrons and their synchrotron photons may be responsible for the peak at higher energies. This synchrotron self-Compton model is contrasted by external Compton models. In the latter, the low-energy photons originate outside the emission volume of the gamma-rays. Possible sources of target photons include: accretion disk photons radiated directly into the jet, accretion disk photons scattered by emission-line clouds or dust in the jet, synchrotron radiation re-scattered back into the jet by broad-line emission clouds, jet emission from an outer slow jet sheet, or emission from faster or slower portions of the jet (Ghisellini & Maraschi 1989; Macomb et al. 1995; Mastichiadis & Kirk 1997; Ghisellini et al. 2005; Georganopoulos et al. 2004).

There are also hadronic models for the TeV emission. An example for a hadronic $\gamma$-ray production mechanism is pion photoproduction from either low-energy synchrotron photons or photons external to the jet (e.g., Mannheim 1993; Mücke et al. 2003). Synchrotron emission from protons in compact regions of the jet is another explanation (Aharonian 2000).

Blazars are known for their variability at X-ray and $\gamma$-ray energies. The X-ray and $\gamma$-ray fluxes can vary rapidly and are often correlated, with a notable exception of orphan TeV flares (e.g., Krawczynski et al. 2004). X-ray flaring epochs lasting many months have been observed as well as sub-hour flares (e.g., Cui 2004). The source of flaring activity has been attributed to internal shocks within the jet (Rees 1978; Spada et al. 2001), ejection of relativistic plasma into the jet (Boettcher et al. 1997; Mastichiadis & Kirk 1997), as well as reconnection events in a magnetically dominated jet (Lyutikov 2003; Giannios et al. 2009).

Constraining blazar jet models generally requires simultaneous observations across the radio to gamma-ray spectrum. However, these probes can be augmented by focusing on the nuances in a particular waveband. Such is the approach here, specifically with X-rays and their variable signals, since the high count rates and good spectral resolution in this band provide powerful additional probes of the jet environment. Note that using the X-ray spectra of TeV blazars can provide constraints on the modeling of the overall SED. The position of the synchrotron peak has become a marker for classes of BL Lac objects (Padovani & Giommi 1995). Low-energy-peaked BL Lac and high-energy-peaked BL Lac designate whether the synchrotron peak is in the IR–optical or UV–X-ray bands, respectively. Monitoring spectral parameters as flaring events evolve gives insight into the mechanics of the emission (Kirk et al. 1998). From their analysis, for simple models involving a single electron population, different hardness ratio (HR) trends will be observed for varying fluxes depending on the timescales of the processes involved. In the HR–flux plane, there will be clockwise movement as time progresses if the high energy component varies faster than the low-energy component, where electron cooling times exceed the acceleration time; this case is more probably sampled below the X-ray band. Counterclockwise motion in the HR–flux plane is predicted if the observation is made near the synchrotron cutoff frequency, specifically when the cooling and acceleration timescales are roughly equal.

In the case of TeV bright blazars like Mrk 421, individual sources have shown both hard and soft lags (e.g., Kataoka et al. 2000; Takahashi et al. 2000; Tanihata et al. 2001; Sato et al. 2008). Such lags are apparent when a light curve is examined in two energy bands (canonically separated at 2 keV). Trends in the count rate do not always occur simultaneously in both energy windows. Features can also be observed first at high energies (soft lag) or first at low energies (hard lag).
The peak energy and curvature of the X-ray spectrum have been shown to be anti-correlated for different acceleration scenarios such as stochastic or energy-dependent acceleration (e.g., Kardeshev 1962; Massaro et al. 2004; Stawarz & Petrosian 2008). X-ray measurements also can provide limits on physical properties of the emitting region such as its size (e.g., $R \approx 10^{15}$ cm; see Tramacere et al. 2009). Thus, although multiwavelength observations are crucial for investigating acceleration and emission processes, careful study of X-ray observations from TeV blazers can give insight into the mechanisms responsible for the populations of charged particles and photons in the jet.

Mrk 421 is a TeV blazar and, at a redshift of $z = 0.031$, it is one of the closest and best-studied BL Lac objects. It was the first extra-galactic TeV source (Punch et al. 1992) and has been the target of many multiwavelength campaigns (e.g., Takahashi et al. 1996; Krawczynski et al. 2001; Rebillot et al. 2006; Gupta et al. 2008; Fossati et al. 2008). The synchrotron peak in Mrk 421’s spectrum ranges from a fraction of a keV to several keV and spectral variability as a function of flux level has been observed (Fossati et al. 2000). In general, the spectrum becomes harder for higher fluxes, both in the X-ray band (e.g., Fossati et al. 2008; Tramacere et al. 2009) and in the gamma-ray regime (Krennrich et al. 2002; Abaronian et al. 2002).

It also now has a well-measured GeV-band spectrum from Fermi’s Large Area Telescope (see Abdo et al. 2009) which provides useful constraints on the high-energy electron population using an inverse Compton signal interpretation. The relationship between the Fermi and Suzaku spectra will be discussed in Section 4.

Takahashi et al. (1996) observed a soft lag (<1.5 keV) in X-rays. When attributed to synchrotron electron lifetimes, the magnetic field strength and electron Lorentz factor were found to be $B \sim 0.2$ G and $\gamma_e \sim 10^6$, respectively. Swift observations indicate that each flare has its own competition between time scales involved with electron acceleration and cooling. The energy spectrum of the electrons associated with the UV–X-ray emission can be described with a curved population (Tramacere et al. 2007; Tramacere et al. 2009). Previous Suzaku observations suggest that the emission contains a steady component and a variable component. The latter may be attributed to localized Fermi I type acceleration in individual shocks, while the former may be due to superposition of shocks at larger distances from the jet or other processes (Ushio et al. 2009).

In this paper, we give the findings from a 4 day observation of Mrk 421 with the X-ray satellite telescope Suzaku in 2008 May. This pre-dates the launch of Fermi. Simultaneous XMM-Newton and VERITAS gamma-ray observations in a separate campaign were described by Acciari et al. (2009). Another paper combines a large number of multiwavelength observations of Mrk 421, including the XMM-Newton, Suzaku, and VERITAS data (Acciari et al. 2010).

We investigate the evolution of spectral parameters over the duration of the observation. The study presented in this paper benefits from the long exposure of 364 ks and the excellent sensitivity of Suzaku over the 0.5–30 keV energy range. Compared to the 2006 Suzaku observation campaign presented by Ushio et al. (2009), the observations presented here reveal the source in a lower flux state. In Section 2, we describe the Suzaku instruments, give the essentials of this observation, and outline the analysis protocol. The results are detailed in Section 3. These are followed in Section 4 by the discussion of the interpretation and implications of the findings, highlighting how the X-ray spectrum and variability impact our understanding of the Mrk 421 jet environment and the particle acceleration properties therein.

2. OBSERVATIONS AND DATA REDUCTION

Suzaku (Mitsuda et al. 2007) is an X-ray observatory with two primary instruments. The X-ray Imaging Spectrometer (XIS) is an imaging X-ray CCD instrument with three operating detectors: two are sensitive from 0.5 keV to 10.0 keV (XIS0 and XIS3), while the backside-illuminated XIS1 extends the low energy range to 0.2 keV (Koyama et al. 2007). Complementary to and co-aligned with the XIS is the Hard X-ray Detector (HXD) which is a well-type instrument composed of GSO scintillator and silicon PIN diodes. The PIN detectors observe in the 12–60 keV energy band, while the GSO can detect up to gamma-ray energies (Takahashi et al. 2007; Kokubun et al. 2007). This observation (ID 703043010) was triggered from a detection by the ground-based atmospheric Čerenkov telescope, VERITAS. Mrk 421 was observed 2008 May 5 02:52 (MJD 54,591) through May 9 08:24 (MJD 54,595). Suzaku has two observation modes which place a source either in the center of the HXD or XIS fields of view. HXD pointing was selected for this observation. The XIS instruments were operated in 1/8 window mode.

2.1. Data Reduction

The XIS and HXD event files were used for this study. Standard reduction and processing were performed using HEASOFT v6.8 and Suzaku tools v15. The files were cleaned with the selection criteria: cutoff rigidity larger than 6 GV/c, Earth rim elevation angle greater than 5° and 20° during the night and day, respectively.

XIS events were extracted from a source region with an inner radius of 35 pixels and an outer radius of 408 pixels. The extent of the inner radius is such that pile-up effects were minimized for the selected events. The background was selected from an annulus outside of the source region, with inner and outer radii of 432 pixels and 464 pixels, respectively. The response matrix and effective area were calculated for each XIS sensor using the Suzaku tools tasks, xissimarfgen and xissimarfgen (Ishisaki et al. 2007). XIS1 data were not included in this analysis; including the XIS1 spectra did not improve the quality of the fits. As the XIS0 and XIS3 have similar responses, their data were summed.

PIN data were extracted from the HXD uncleaned event files after standard screening. The tuned background model supplied by the Suzaku team was used for non-X-ray background events. The source spectra were corrected for deadtime using hxdtdcor. The PIN light curves were deadtime-corrected bin-by-bin (after incorporating 4–6 ks bins) using pseudo events generated in orbit. The background and spectra light curves were corrected for their $10 \times$ oversampling rate. We estimate the cosmic X-ray background (CXB) contribution to the PIN background using the model given in Gruber et al. (1999), which is folded with the PIN response to estimate the CXB rate.

3. TEMPORAL AND SPECTRAL RESULTS

3.1. Light Curves

We plot the time history of the observation in Figure 1. Light curves are given in two energy bands for each instrument: 0.5–2.0 keV and 2.0–10.0 keV for the XIS; 10.0–20 keV and 20–30 keV for the PIN. The three lowest energy bands include...
similar count rate evolution throughout the observation, while the highest energy band does not have significant changes. Overall, the rates decrease by up to a factor of 2 over the course of the observation. Rates decrease from $\sim$50 to $\sim$20 counts s$^{-1}$ in the 0.5–2 keV range and 0.16 to 0.13 counts s$^{-1}$ in the 20–30 keV band. The general decline in rates is marked by several shorter duration flares occurring at 80 ks, 120 ks, 140 ks, 260 ks, 310 ks, and 340 ks after the start of the observation.

The light curves begin with a rapid decline in rates for the initial 20 ks of the observation. There is a general leveling off with some small variations in rates over the next 100 ks. A strong $\sim$25 ks flare is then seen which brings rates close to their original level. This flare is shorter in duration for higher energy bands. The rates then smoothly decline for $\sim$30 ks. During this time, a flare is observed in the 12–20 keV band, but not in any other bands. There is then a second large flare which is seen in the three lower energy ranges. The last 50 ks of the observation has two small flares spanning the period.

We investigate the time evolution of the HR of the XIS events. It is convenient to divide the observational window into two bands, 0.5–2 keV ($a$) and 2–10 keV ($b$), and define the HR as either the ratio of counts ($b/a$), or the ratio of the difference and sum of counts ($/(b-a)/(b+a)$), a standard protocol. Here, we use the former definition of HR. This differs slightly from the approach of Tramacere et al. (2009), who use the spectral index at 1 keV to prescribe an HR.

Figure 2 shows the 0.5–2.0 keV (top) and 2–10 keV (middle) rates, and the corresponding HR (bottom). At the start of the observation, the rates decline quickly as does the HR. At a time of $\sim$20 ks, the HR begins to increase while the rates in both bands continue to decrease then stabilize for a duration of $\sim$8000 s. For the remainder of the observation, the HR follows the flux. It becomes harder for larger fluxes so that the HR versus time plot largely reproduces the features in the light curves. Using the XIS response and xspec, we simulate spectra for a simple power-law model using photon indices between 2.2 and 2.5. We calculate the HR measured by XIS for these simulated observations and indicate the corresponding position in the lower panel of Figure 2 (horizontal dotted lines) for comparison with the measured HRs.

The vertical lines in Figure 2 are to aid the eye in comparing trends between the rates in the two energy bands and the HR. The first vertical line indicates when the HR changes from decreasing to increasing trend while the count rates continue to decrease. The second vertical line shows a time when the rates and the HR level off and drop during a small flare. The third vertical line marks the peak of a large flare (Flare 1) in both energy bands. However, it is obvious that the HR peaked $\sim$20 ks prior to the peak in rates. The last vertical line is again placed at a peak (Flare 2) in the count rates. For this flare, the HR peak is located closer in time to the peak rate, however, the subsequent decrease in the HR is delayed compared to the rate decrease. The shaded gray region in Figure 2 denotes the observation window for the VERITAS campaign described in Acciari et al. (2009; see also Acciari et al. 2010).

3.2. Spectra

During fitting, events with deposited energy between 1.5 keV and 2.5 keV were excluded from the XIS data set due to uncertainties in the instrument response (Ushio et al. 2009). Events with energy between 10 keV and 25 keV were included from the PIN data. The resulting spectrum was fit with a galactic absorption $\times$ broken power law. The galactic absorption parameter, $n_H$, was kept constant at the value of $1.61 \times 10^{20}$ cm$^{-2}$ acquired from the CIAO tool Colden. Once the normalization parameter was fit for the model, it was frozen while the low-energy photon index ($\Gamma_1$), break energy ($E_b$), and high-energy photon index ($\Gamma_2$) were fit independently. Finally, all parameters were simultaneously fit. Note that while similarly good spectral fits were produced using power-law with exponential cutoff models for a few of the results presented here, broken power-law fits were superior to other spectral functions for the majority of time intervals. For broken power-law fits, the average reduced $\chi^2$ is 1.1 for 41 degrees of freedom (dof) with a standard deviation of 0.34, while power law with exponential cutoff fits produced

3 http://cxc.harvard.edu/toolkit/colden.jsp
Figure 3. XIS and PIN observed spectra are given for the first ~20 ks (high) and the final ~20 ks (low) of the observation (top panel). The bottom panel plots the ratio, Rate\textsubscript{high}/Rate\textsubscript{low}, as a function of energy. A factor of ~2 count rate decrease can be seen at most energies between 3 keV and 20 keV while smaller ratios occur at lower energies.

average reduced $\chi^2$ of 4.05 for 42 dof with a standard deviation of 2.1.

Comparing the spectra at the endpoints of the observation can give insight into the overall evolution of the emission as a function of energy. The upper panel of Figure 3 plots the XIS and PIN spectra for the first as well as final ~20 ks of the observation. The best-fit broken power-law models are also shown. The best-fit parameters for the start of the observation are $\Gamma_1 = 2.25 \pm 0.01$, $\Gamma_2 = 2.61 \pm 0.01$, $E_B = 2.29 \pm 0.09$ keV, and normalization of 0.367 ± 0.001 counts s\textsuperscript{-1} keV\textsuperscript{-1} producing a reduced $\chi^2$ of 1.70. The best-fit parameters for the end of the observation are $\Gamma_1 = 2.39 \pm 0.03$, $\Gamma_2 = 2.62 \pm 0.01$, $E_B = 2.2 \pm 0.3$ keV, and normalization of 0.206 ± 0.001 counts s\textsuperscript{-1} keV\textsuperscript{-1} producing a reduced $\chi^2$ of 1.19. It is apparent that the rates do decline over the course of the observation. The lower panel shows the HR (Rate\textsubscript{high}/Rate\textsubscript{low}), highlighting beginning and end intervals of the 364 ks observation. The largest values for the ratio occur at ~8–10 keV, indicating an overall slight softening trend. Observe that these spectra are generally considerably steeper than those for the intense flare activity reported for 2006 Swift observations of Mrk 421 in Tramacere et al. (2009).

In addition to analyzing spectra at the onset and end of the observation, we consider 12 smaller time bins describing the entire observation and fit the corresponding XIS and PIN spectra with a broken power-law model. The chance probability associated with the reduced $\chi^2$-values of the fits have values between 0.01 and 0.96, indicating satisfactory fits. The best-fit parameters are given as a function of time in Figure 4. It is not possible to fit the time-averaged spectrum satisfactorily with a power law, power law with high energy cutoff, or broken power-law models. This is not unreasonable due to the wide range of flux and spectral variability observed in the shorter time intervals.

Figure 5 investigates the correlations between flux normalization, $\Gamma_1$, $\Gamma_2$, and $E_{br}$ for the 12 time intervals in Figure 4. The upper left panel shows that $\Gamma_1$ increases somewhat for larger $E_{br}$ values, which is also the case for $\Gamma_2$ and $E_{br}$ (lower left panel); the scatter in these trends is large. The upper right panel shows no correlation between $E_{br}$ and the normalization. Finally, the lower right panel demonstrates that the two photon indices increase and decrease together, as would be expected with slight variations in the maximum energy of the radiating particles. Insights gleaned from these correlation plots are discussed in Section 4.

Further understanding can be provided by exploring HR variations during flares. In Figure 6, HR–flux diagrams are given for the two most prominent flares (1.5 × 10\textsuperscript{5} s and 2.5 × 10\textsuperscript{5} s; Figure 1). The left panels show the light curves in two energy bands from XIS observations. The higher energy rates have been multiplied by a factor of 3 for clarity. We see that for the Flare 1 (top panels), there is initial clockwise motion which quickly changes to a larger counterclockwise arc through the HR–flux plane. Flare 2 also shows both clockwise and counterclockwise motion but in a smaller figure 8 pattern. These characteristics of spectral hysteresis are similar to a subset of the Swift data reported in Tramacere et al. (2009) for the 2006 observations of Mrk 421 flares. The HR–flux trend of an observation can be an indicator of relative time scales for processes involved with acceleration and emission (see Kirk et al. 1998; Tramacere et al. 2009, and references therein for a discussion). For clockwise motion, the cooling time will be longer than the acceleration time. The two timescales are comparable for counterclockwise trends.

4. SPECTRAL INTERPRETATION AND DISCUSSION

One of the key results from this observation campaign is that we observe different spectral evolution for similar flares. The different spectral evolutions during different flares exclude models in which flux and spectral variations are caused exclusively by variations of the Doppler beaming factor. Furthermore, they do not concur with simple models where particles are always accelerated with the same spectral index and cool radiatively. Therefore, we conclude there have to be intrinsic variations of the somewhat steep X-ray spectra.

In the following interpretative discussion, two scenarios will be addressed in turn, after the issue of Doppler boosting variations is first touched upon. First, the case that radiative cooling does not lead to a steepening of the observed X-ray energy spectra is considered. Subsequently, we turn to the scenario of efficient radiative cooling that spawns a steepening of the observed spectral indices by $\Delta\Gamma = 1/2$. We remark that several VERITAS TeV gamma-ray observations were taken during our Suzaku observations (see Acciari et al. 2009, 2010). These observations revealed modest TeV gamma-ray flares, demonstrating...
that the synchrotron spectral power dominated the inverse Compton emissive power, which is also the situation for much earlier Whipple-era observations (e.g., see the broadband data depiction in Inoue & Takahara 1996). The following discussion can thus safely neglect complications arising from inverse Compton cooling in the Klein–Nishina regime, which in other circumstances can modify the distribution of the highest energy particles, and therefore also the shape of the X-ray synchrotron continuum.

To provide context for the results of this paper in the light of other multifrequency observations, we note that it is likely that the radio emission observed from Mrk421 does not come from precisely the same spatial region as the X-ray emission. For BL Lac type objects, no convincing radio/X-ray correlation has ever been established. For leptonic models that explain the observed X-ray emission without giving a measurable radio flux, see Rebillot et al. (2003) and Krawczynski et al. (2001). The discussion here therefore focuses on explaining the

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**Figure 4.** This figure plots the best-fit parameters and 1σ confidence ranges for different times during the observation using a broken power-law model. The panels (top to bottom) give the evolution of the flux normalization (photons s⁻¹ keV⁻¹), Γ₁, Γ₂, E_B (keV).

**Figure 5.** Best-fit parameters from the four panels of Figure 4 are plotted against each other. The upper left figure plots the correlation of E_B and Γ₁. The lower left panel shows the relationship between E_B and Γ₂. The upper right panel gives E_B vs. flux normalization which shows no correlation. The lower right panel shows the relationship between Γ₁ and Γ₂. The two photon indices increase and decrease together.
high energy emission from electrons close to the high energy cutoff of the electron energy spectrum. While multiwavelength SED modeling of blazars with radio-to-X-ray synchrotron and gamma-ray inverse Compton signals typically constrains the approximate maximum Lorentz factor of the electrons, the mean magnetic field strength, and the bulk Doppler factor $\delta$ of the jet (e.g., see Bednarek & Protheroe 1997; Mastichiadis & Kirk 1997), SED fluctuations augment these by probing different jet environmental quantities. This is the focus here, and X-ray observations afford stronger diagnostics than do the GeV and TeV bands due to their high count rates. For example, typical variability in Fermi-LAT data on blazars samples timescales of a few days to a week at best (Abdo et al. 2010b) when acquiring sufficient count statistics. TeV gamma-ray energy spectra with spectral index errors $<0.1$ can be acquired on short ($\sim10$ minutes) time scales—but require extremely strong flares.

To begin the interpretive focus on the X-ray variability principally, adjustments of the spectral indices and HRs can...
be generated by fluctuations in the Doppler beaming factor $\delta$ during flares. Such $\delta$ variations can arise in bent jets, such as the scenario envisaged for Fermi-LAT and other wavelength observations of the quasar 3C 279 (Abdo et al. 2010a). Consider the correlation plots in Figure 5. In the absence of other influences, changes in $\delta$ should manifest themselves as a scaling of the break energy $E_{br} \propto \delta$ (blueshifting) and an associated scaling of the flux at $E_{br}$ as $\delta^4$. This correlation should hold approximately even if the 0.2–10 keV window samples a portion of a larger SED curvature. It is clearly not seen in the upper right panel of Figure 5, indicating that some other environmental fluctuation is operative. If the SED curvature is broad, one might expect that higher break energies in the fits will correlate with lower $\Gamma_1$. The opposite is suggested in the upper left panel of Figure 5, but the scatter is large, and the $E_{br}$ range is small. In terms of the HR–flux diagrams in Figure 6, pure Doppler factor $\delta$ fluctuations should yield a strong correlation between the HR and the count rate below 2 keV: essentially a diagonal trace from lower left to upper right. This is clearly not seen for Flare 1. There is more of an indication for Flare 2, but significant deviations from a clean correlation occur when taking into account the evolutionary track. Accordingly, something deeper than just simple Doppler boosting variations must be active in the jet environment, and our attention turns to the particle acceleration properties in shocks within the Mrk 421 jet.

The observed spectral fluctuation signatures are therefore interpreted now in the light of expectations from diffusive shock acceleration theory. This logical step can be taken because the power law is both well established below $E_{br}$ and is considerably flatter than the steeper spectra seen in the TeV band that might typify the onset of a cutoff. If the spectral indices 2.2 $\lesssim \Gamma_1 \lesssim 2.5$ identified in Figures 5 and 6 are attributed to synchrotron emission from a particle distribution $dN/e/d\gamma_e \propto \gamma_e^{-\sigma}$ (below a maximum Lorentz factor cutoff $\gamma_{max}$), then for uncooled synchrotron scenarios, $\Gamma_1 = (\sigma + 1)/2$. These cases are where the accelerated population is continually replenished in the emission region on timescales inferior to the synchrotron cooling timescale $t_{syn} = 4\pi m_e c/[(\sigma^2 B^2)\gamma_e^{-1}]$. Observe that $t_{syn} \sim 1$ hr for $B = 0.1$ G and $\gamma_e \sim 10^7$, parameters that would place the synchrotron turnover at $\sim 1500$ keV. In this scenario, the acceleration timescale needs to be comparable to the flare duration or shorter, while $t_{syn}$ needs to exceed the flare timescale, a situation that occurs for lower $\gamma_e$ that can move the synchrotron turnover down to the Suzaku window. For such an uncooled acceleration picture, the X-ray index in any time interval leads to a constraint on the electron index $\sigma$ and we find $3.4 \lesssim \sigma \lesssim 4$. The physical conditions in the Mrk 421 jet environment that can generate $\sigma$ in this range can be assessed using the Monte Carlo simulational modeling of Baring & Summerlin (2009) and Baring (2010), and earlier by Ellison & Double (2004), of particle acceleration at relativistic shocks. These works provided a useful and expansive complement to earlier semi-analytic investigations of Kirk & Schneider (1987) and Kirk & Heavens (1989) that employed eigenfunction techniques to solve the diffusion-convection equation at mildly relativistic shocks.

The spectral index parameter space explored in these simulational studies clearly indicated that values of $\sigma > 3$ are appropriate only for so-called superluminal shocks, i.e., those where $u_i/\cos \Theta_{bl} > c$. Here $u_i$ is the component of the upstream flow speed normal to the shock in its rest frame. For the relativistic outflows commonly invoked in blazar jets, one naturally expects $u_i \sim c$. Also, $\Theta_{bl}$ is the angle the magnetic field vector makes to the shock normal in the upstream fluid rest frame. Therefore, superluminal (and oblique, $\Theta_{bl} > 0^\circ$) conditions in Mrk 421’s jet would naturally be expected. However, Baring & Summerlin (2009) also observed that to generate $\sigma > 3$, it would be necessary for the field turbulence in the shock neighborhood to not be too strong, perhaps limiting field fluctuations to $\delta B/B \lesssim 0.1$, so that particle diffusion is not too near the isotropic Bohm limit (essentially occurring for $\delta B/B \sim 1$). This is an interesting environmental constraint that lowers the expected acceleration time $t_{acc} \sim 1G$ due to the inefficient trapping of charges in oblique shocks, a property that is directly responsible for steeper power laws with $\sigma \gtrsim 3$.

Consider instead a strongly cooled synchrotron emission picture, where the shock injects relativistic particles into a larger region where the synchrotron cooling timescale exceeds the injection timescale. Invoking such to explain the Suzaku power-law indices, one infers $\sigma = 2(\Gamma_1 - 1)$ for the shock acceleration spectral index, since synchrotron cooling steepens the electron power law by an index of unity; the index then falls in the range $2.4 \lesssim \sigma \lesssim 3$ for the data reported in Figures 5 and 6. This still lies in the parameter space for superluminal shocks (Baring & Summerlin 2009), but requires somewhat stronger field turbulence than for the uncooled case, perhaps in the range $\delta B/B \lesssim 0.3$. Again, Bohm-limited diffusion is not indicated. It is noted in passing that these claims are predicated on acceleration theory results generated for small angle scattering (i.e., pitch angle diffusion); if $\delta B/B \sim 1$ is considered, then one anticipates that larger angle deflections of charges will be active, resulting in much flatter spectra (e.g., Ellison et al. 1990; Stecker et al. 2007) that are incongruent with the Mrk 421 Suzaku data presented here. Such a large angle scattering regime may be more appropriate for the 2006 Swift observations of the intense flare in Mrk 421 (Tramacere et al. 2009), and for some flat spectrum gamma-ray sources in the Fermi-LAT database (Abdo et al. 2009).

For Mrk 421, the 2009 observations by Fermi-LAT that are not contemporaneous with the Suzaku data presented here yield $\Gamma_1 \sim 1.78$ (Abdo et al. 2009). If this signal constitutes inverse Compton emission by uncooled electrons at Lorentz factors below $\gamma_e (< \gamma_{max})$, then one infers $\sigma \sim 2.56$, not dissimilar to the Suzaku inference for strong cooling just above. Given that this GeV-band spectrum probably originates from electrons that emit synchrotron photons below the X-ray window, and that the steeper TeV spectrum ($\Gamma_\gamma \sim 2.91$ in the contemporaneous VERITAS data presented in Acciari et al. 2009) provides an approximate inverse Compton image of the X-ray synchrotron signal (with $\Gamma_2 \sim 2.5–2.9$ here), one expects the inferred $\sigma$ for the Fermi data should be slightly lower than that for the Suzaku observations. Note also that historically, the radio spectrum for Mrk 421 is flatter still, at $\Gamma_{rad} \sim 1.1–1.3$ (e.g., see Makino et al. 1987), suggesting $\sigma \sim 1.2–1.6$ for the electrons radiating at these frequencies. Taken together with the gamma-ray data, a picture emerges that the radiating lepton distribution might be injected with a “convex” distribution, i.e., with $\sigma$ an increasing function of energy. Yet, care must be taken to explore the influence of non-cospatiality for the origin of the various emission components, and the role of synchrotron self-absorption, before diagnosing such a curvature in the injection distribution.

Let us delve deeper into a comparison between the cooled and uncooled emission scenarios. It is possible to envisage a cospacial competition between acceleration and synchrotron cooling, a paradigm that is commonly accepted in models of
X-ray emission in Galactic supernova remnants (SNRs). While this can generate the observed variability in both flux and spectral index, unless diffusion in shock-layer turbulence is incredibly inefficient, the requirement that a cooling-limited synchrotron turnover fall in the Suzaku X-ray window constrains the shock speed $u_1$ to values around 0.01$c$, independent of the strength of $B$, provided that the acceleration process is gyroresonant, which is the prevailing paradigm. This assertion can be justified using results from the discussion of cooling-limited SNR shock acceleration in Baring et al. (1999). Equation (12) therein indicates that the acceleration rate gives $d\gamma_e/ dt \propto (u_1/c)^2 B/(\eta mc)$, where the ratio $\delta = \lambda/r_g \geq 1$ of the particle’s mean free path $\lambda$ to its gyroradius $r_g$ measures the departure from isotropic Bohm diffusion ($\eta = 1$, i.e., $\delta B/B \sim 1$). This can be equated to the synchrotron loss rate $|\dot{\gamma_e}/dt| \propto \gamma_e^2 B^2$ in the comoving frame of the jet. The resulting electron Lorentz factor $\gamma_e \equiv \gamma_c \propto u_1(\eta B)^{-1/2}$ for cooling-limited acceleration can be inserted into the textbook formula for the characteristic synchrotron energy to yield a synchrotron peak/cutoff energy, that is independent of the field strength:

$$E_{\text{syn}} \propto \frac{\delta}{\eta} \frac{u_1}{c}^2 \frac{m_e c^2}{\alpha}.$$  

(1)

Here $\alpha = \delta^2/(\eta c^2)$ and the blueshift due to Doppler beaming has been included. For $\delta = 1$, the $u_1 = c$, $\eta = 1$ limit of this is around 50 MeV, as was highlighted in De Jager et al. (1996) for considerations of gamma-ray emission at relativistic pulsar wind nebular shocks; see de Jager & Baring (1997) for a compact presentation of this critical energy.

To move $E_{\text{syn}}$ into the classic X-ray band one has to set $u_1 \sim 0.01c$ if $\eta \gtrsim 1$ and lower still if $\delta > 1$. This lower shock speed is an attractive value for SNRs, but is clearly too small for blazar jet contexts. It is possible to adjust $\eta$ to fix $u_1 \sim c$, which quickly leads to fitting values $\gamma_e \sim 10^5$, thereby dramatically reducing the rapidity of the acceleration process. This was the approach of Inoue & Takahara (1996) when exploring multiwavelength modeling of Mrk 421 spectra (they required even higher values $\gamma_e \sim 10^6$ for their 3C 279 case study), who assumed $\delta \sim 10$. In the light of refined studies of acceleration at relativistic shocks, this is unsatisfactory on three counts. First, the parameter space of shocks that would generate indices $\sigma$ that would accommodate the Suzaku indices is extremely constrained to the subluminal/superluminal boundary (e.g., see Baring 2010). Next, requiring $\eta > 10^4$ leads to extraordinarily inefficient injection of particles into the acceleration process (e.g., Baring & Summliner 2009), imposing uncomfortable constraints on blazar energetics. Finally, such large values of $\eta$ define essentially laminar fields that are not expected in shocks, which are inescapably turbulent. Hence, it is difficult to fine-tune a synchrotron-cooling-limited turnover in the X-ray band in the blazar model context.

In contrast, it is quite possible that a cooling break can be situated below the X-ray band, provided that the acceleration and cooling regions are spatially distinct. This is a preferred paradigm in many blazar models. Such a strongly cooled case corresponds to static or impulsive acceleration at a shock, generating non-thermal electrons up to the maximum Lorentz factor (which can be $\gamma_c \gtrsim 10^6$ on timescales of a few seconds for $\eta \sim 1$ and $B \sim 0.1G$), followed by escape from the shock environs and subsequent gradual cooling in a remote and more extended region that is defined by the competition between spatial diffusion/convection and radiative cooling. Flux and index variability driven by cooling effects would then tend to be muted by spatial and temporal convolutions. Moreover, spectral cooling breaks, if situated in the optical/UV band, would correspond to Lorentz factors $\gamma_c \sim 10^3$–$10^4$ and therefore yield cooling times of the order of days or longer. Hence, the spectral variations on timescales of a few hours reported here very probably reflect intrinsic fluctuations in the acceleration/injection process, as opposed to spatial inhomogeneities such as magnetic field clumping in the cooling region. The spectral hysteresis evinced in Figures 5 and 6 possesses some similarities to, and significant differences from that envisaged in the competitive acceleration/cooling model of Kirk et al. (1998). 

Flare 1 seems to suggest that alterations in shock conditions precipitate an increased injection rate $\dot{n}_e$ (or an increased field) before flattening the distribution (lowering the index $\sigma$), the system subsequently relaxing via reducing the injection rate or field strength and finally displaying signs of an incipient increase in $\sigma$. Field turbulence variations should drive injection and $\sigma$ changes that contribute to both flux and HR alterations. Flare 2 encapsulates another level of complexity, defying simple description. 

To summarize, given these cooling/acceleration considerations, it seems likely that the variations depicted in Figures 5 and 6 signify changes in the lepton acceleration at the relativistic shocks contained in the Mrk 421 jet, perhaps with a smaller contribution from Doppler beaming fluctuations. The acceleration fluctuations are easily produced from a theoretical standpoint by just modest or small changes to the level of field turbulence, the mean field direction and amplitude, or the local density encountered in the shock environs as it traverses jet material. This claim is underpinned in part by the broad-ranging spectral index phase space plots presented in Baring & Summerlin (2009) and Baring (2010), together with their discussion of correlated injection efficiencies.

Finally, even though properties of the acceleration process may cause spectral variations in the X-ray band, we reiterate that most of the conclusions from earlier multiwavelength leptonic modeling work are still valid (e.g., Krawczynski et al. 2001). A magnetic field of $\sim 0.2G$ is still needed so that electrons can emit a good fraction of their energy on $\sim 1$ hr time scales. Also, $\gamma_{\text{max}}$ and $\delta/B$ are still constrained by the relative peak positions of the SEDs in the X-ray and gamma-ray regimes. The inference of variations of the parameters of the acceleration process in jet shocks from observed X-ray SED fluctuations is a subtlety that does not substantially modify these more global parameters inferred from the broadband SED modeling, but does directly impact the relative apportionment of acceleration and cooling, in part through constraints imposed on $\eta = \lambda/r_g$.

5. SUMMARY

We present the results from a four day Suzaku observation of Mrk 421 while in a flaring state. The 0.5–30 keV flux decreased by a factor of 2 during the course of the observation. We find good agreement when fitting spectra from isolated time intervals with a galactic absorption + broken power-law model. Trends in the HR–flux plane indicate that there are different timescales for competing processes which differ from flare to flare and for different flux levels. The X-ray spectral index changes by $\sim 0.2$. However, the spectral evolution seems not to be related to the phase of a flare. The erratic relation between the light curves and the spectral indices suggests constraints on the interpretation of the shocked jet environment.
In the literature, the past observations have often been explained by invoking the competition of the acceleration and cooling time scales. However, it seems improbable that the timescales of acceleration and cooling are similar, since this would require jet shock speeds of the order of 0.01c, and that the relative importance of shock acceleration and subsequent synchrotron cooling differs from flare to flare. We suggest here that it is more likely that the Suzaku data properties reported here are due to intrinsic changes in the acceleration process at relativistic shocks in the jet, producing electron distributions with varying spectral indices and changing maximum energies.

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REFERENCES
Abdo, A. A., et al. 2009, ApJ, 707, 1310
Abdo, A. A., et al. 2010, ApJ, 707, 1310
Acciari, V. A., et al. 2009, ApJ, 703, 169
Acciari, V. A., et al. 2010, ApJ, submitted
Aharonian, F. A. 2000, New Astron., 5, 377
Aharonian, F. A., et al. 2002, A&A, 393, 89
Baring, M. G. 2010, Adv. Space Res., in press (arXiv:1002.3848)
Baring, M. G., Ellison, D. C., Reynolds, S. P., Grenier, I. A., & Goret, P. 1999, ApJ, 513, 311
Baring, M. G., & Summerlin, E. J. 2009, in AIP Conf. Proc., 1183, Shock Waves...
Bednarek, W., & Protheroe, R. J. 1997, MNRAS, 292, 646
Boettcher, M., Mause, H., & Schlickeiser, R. 1997, A&A, 324, 395
Cui, W. 2004, ApJ, 605, 662
De Jager, O. C., & Baring, M. G. 1997, in AIP Conf. Proc. 410, Proc. 4th Compton Symp, ed. C. D. Dermer, M. S. Strickman, & J. D. Kurfess (Melville, NY: AIP), 171
De Jager, O. C., Harding, A. K., Michelson, P. F., Ncl, H. I., Nolan, P. L., Sreekumar, P., & Thompson, D. J. 1996, ApJ, 457, 253
Ellison, D. C., & Double, G. P. 2004, Astropart. Phys., 22, 323
Ellison, D. C., Jones, F. C., & Reynolds, S. P. 1990, ApJ, 360, 702
Fossati, G., et al. 2000, ApJ, 541, 166
Fossati, G., et al. 2008, ApJ, 677, 906
Georganopoulos, M., & Kazanas, D. 2004, ApJ, 604, L81
Ghisellini, G., & Maraschi, L. 1989, ApJ, 340, 181
Ghisellini, G., Tavecchio, F., & Chiaberge, M. 2005, A&A, 432, 401
Giannios, D., Uzdensky, D. A., & Begelman, M. C. 2009, MNRAS, 395, L29
Gruber, D. E., Matteson, J. L., Peterson, L. E., & Jung, G. V. 1999, ApJ, 520, 124
Gupta, A. C., Acharya, B. S., Bose, D., Chitnis, V. R., & Fan, J. 2008, Chin. J. Astron. Astrophys., 8, 395
Homan, D. C., Roopeshi, O., Wardle, J. C., & Roberts, D. H. 2001, ApJ, 549, 840
Inoue, S., & Takahara, F. 1996, ApJ, 463, 555
Ishisaki, Y., et al. 2007, PASJ, 59, S113
Jokipii, J. R. 1987, ApJ, 313, 842
Kataoka, J., Takahashi, T., Makino, F., Inoue, S., Madejski, G. M., Tashiro, M., Urry, C. M., & Kubo, H. 2000, ApJ, 528, 243
Kirk, J. G., & Heavens, A. F. 1989, MNRAS, 239, 995
Kirk, J. G., Rieger, F. M., & Mastichiadis, A. 1998, A&A, 333, 452
Kirk, J. G., & Schneider, P. 1987, ApJ, 315, 425
Koyama, K., et al. 2007, PASJ, 59, 23
Krawczynski, H., et al. 2001, ApJ, 559, 187
Krawczynski, H., et al. 2004, ApJ, 601, 151
Krennrich, F., et al. 2002, ApJ, 575, L9
Lyutikov, M. 2003, New Astron. Rev., 47, 513
Makino, F., et al. 1995, ApJ, 449, L99
Makino, F., et al. 1997, ApJ, 313, 662
Mannheim, K. 1993, A&A, 269, 67
Massaro, E., Perri, M., Giommi, P., Nesci, R., & Verrecchia, F. 2004, A&A, 422, 103
Mastichiadis, A., & Kirk, J. G. 1997, A&A, 320, 19
Mitsuda, K., et al. 2007, PASJ, 59, S9
Mücke, A., Protheroe, R. J., Engel, R., Rachen, J. P., & Stanev, T. 2003, Astropart. Phys., 18, 593
Padovani, P., & Giommi, P. 1995, MNRAS, 277, 1477
Piner, B. G., & Edwards, P. G. 2005, ApJ, 622, 168
Punch, M., et al. 1992, Nature, 358, 477
Rebillot, P. F., & The VERITAS Collaboration. 2003, ICRC (Trukuba), 5, 2599
Rebillot, P. F., et al. 2006, ApJ, 641, 740
Rees, M. J. 1978, MNRAS, 184, 61
Sato, R., Kataoka, J., Takahashi, T., Madjeski, G. M., Rugamer, S., & Wagner, S. J. 2008, ApJ, 680, L9
Spada, M., Ghisellini, G., Lazzati, D., & Celotti, A. 2001, MNRAS, 325, 1559
Stawarz, L., & Petrosian, V. 2008, ApJ, 681, 1725
Stecker, F. W., Baring, M. G., & Summerlin, E. J. 2007, ApJ, 667, L29
Takahashi, T., et al. 1996, ApJ, 470, L89
Takahashi, T., et al. 2000, ApJ, 542, L105
Takahashi, T., et al. 2007, PASJ, 59, S55
Tanihata, C., Urry, C. M., Takahashi, T., Kataoka, J., Wagner, S. J., Madejski, G. M., Tashiro, M., & Kouda, M. 2001, ApJ, 563, 569
Tramacere, A., Giommi, P., Perri, M., Verrecchia, F., & Tosti, G. 2009, A&A, 501, 3
Tramacere, A., Massaro, F., & Cavaliere, A. 2007, A&A, 466, 521
Ushio, M., et al. 2009, ApJ, 699, 1694