AN OCCULTATION EVENT IN CENTAURUS A AND THE CLUMPY TORUS MODEL

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ABSTRACT

We have analyzed 16 months of sustained monitoring observations of Centaurus A from the Rossi X-Ray Timing Explorer to search for changes in the absorbing column in the line of sight to the central nucleus. We present time-resolved spectroscopy which indicates that a discrete clump of material transited the line of sight to the central illuminating source over the course of ~170 days between 2010 August and 2011 February with a maximum increase in the column density of about $8.4 \times 10^{22}$ cm$^{-2}$. This is the best quality data of such an event that has ever been analyzed with the shape of the ingress and egress clearly seen. Modeling the clump of material as roughly spherical with a linearly decreasing density profile and assuming a distance from the central nucleus commensurate with the dusty torus, we found that the clump would have a diameter of $(1.4$–$2.4) \times 10^{15}$ cm with a central number density of $n_{H} = (1.8$–$3.0) \times 10^{7}$ cm$^{-3}$. This is consistent with previous results for a similar (though possibly much longer) occultation event inferred in this source in 2003–2004 and supports models of the molecular torus as a clumpy medium.

Key words: galaxies: active – galaxies: individual (Cen A) – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Centaurus A (Cen A hereafter) is one of the closest and consequently one of the brightest active galactic nuclei (AGNs) in our sky. High-resolution data from infrared and X-ray observatories (such as Spitzer and Chandra) have revealed many details about the structure of its prominent jets as well as the core of the nucleus. Cen A has proved to be an excellent laboratory for studying the properties of blazar jets, however, it also displays certain X-ray properties characteristic of a Seyfert galaxy, likely due to its orientation. For example, X-ray spectroscopy shows a prominent Fe line at 6.4 keV originating in cool material far from the central nucleus (Evans et al. 2004) and strong absorption in the line of sight. Broad optical emission lines have never been detected in this source, marking it as a Seyfert 2. A search for hidden broad lines through polarized scattered light by Alexander et al. (1999) ruled out the existence of a hidden broad-line region (BLR).

Between the launch of the Rossi X-Ray Timing Explorer (RXTE) in 1996 and 2009 February, Cen A was observed 13 times, each an enhanced exposure of ~10–100 ks. Rivers et al. (2011) performed spectral analysis on these data in the 3–100 keV band to measure long-term average spectral properties of Cen A, such as the photon index (Γ = 1.83±0.01) and the equivalent H column density ($N_{H} = (16.9 \pm 0.3) \times 10^{22}$ cm$^{-2}$), and also confirming the lack of a Compton reflection hump in this source. Rothschild et al. (2011) analyzed the individual Cen A observations, examining both spectral and temporal characteristics of this source. From these analyses it was discovered that for three observations between 2003 March and 2004 February, the column density of cold material along the line of sight to the nucleus increased by ~60%, from $16 \times 10^{22}$ cm$^{-2}$ to $26 \times 10^{22}$ cm$^{-2}$. From this it was inferred that a clump of material may have passed through the line of sight at a distance commensurate with the molecular torus. Such an event is consistent with clumpy torus models such as that developed by Nenkova et al. (2008a, 2008b). However, there were only three data points in this interval and therefore the physical parameters of the inferred clump, such as size, number density, and shape, were loosely constrained at best.

Similar short-term increases and decreases in $N_{H}$ have been seen previously in a number of AGNs, notably MCG–6-30-15 (McKernan & Yaqoob 1998), NGC 4051 (Guainazzi et al. 1998), NGC 3227 (Lamer et al. 2003), NGC 3516 (Turner et al. 2008), and NGC 1365 (Risaliti et al. 2009). McKernan & Yaqoob (1998) posited that a small clump of material was occulting a complex source for ~100 ks, causing changes in the measured covering fraction of the absorber. Risaliti et al. (2009) analyzed a 60 ks XMM-Newton observation of NGC 1365, finding very rapid changes in $N_{H}$ on the order of only a few hours. From the short duration of these events they inferred that the material must be quite close to the central nucleus. Further analysis performed by Maiolino et al. (2010) with a 300 ks Suzaku observation confirmed these rapid variations and attributed them to comet-shaped BLR clouds transiting the line of sight on timescales of ~50–100 ks. Note that most of these did not have the advantage of continuous monitoring over timescales of days to months, however, Lamer et al. (2003) were able to fit a β density profile to explain the smooth increase and decrease in $N_{H}$ for NGC 3227 over about 300 days as seen with RXTE monitoring.

A sustained monitoring campaign of Cen A with RXTE began on 2010 January 1, with ~1 ks snapshots every two days. One goal of this observing campaign was to better quantify variation in the column density in this source and to search for additional evidence of transits by discrete clumps of material, with the ability to place better constraints on their physical characteristics. To that end we have analyzed the RXTE observations of Cen A from the monitoring campaign, beginning 2010 January 1 up through 2011 April 20. In this Letter, we present the results of this analysis with data reduction and analysis methods in Section 2 and a discussion of our results in Section 3.

2. DATA REDUCTION AND ANALYSIS

We analyzed 228 ~ 1 ks snapshots of Cen A with RXTE's Proportional Counter Array (PCA; Jahoda et al. 2006). For
and solar abundances from Wilms et al. (2000). Fitting clump version 12.5.1k with cross-sections from Verner et al. (1996) Roth 2011) we extracted PCA STANDARD-2 data all PCA data extraction and analysis we used HEASOFT IDL version 6.3. Uncertainties on spectral fit parameters were calculated using a point-to-point variance method (Vaughan & Edelson 2001; Markowitz et al. 2003) at the 1σ level for all parameters. This method was appropriate for our analysis since the normal method tends to overestimate errors due to the background modeling for short observations such as ours.

We analyzed PCA spectra in ten-day intervals with total exposures of 3–6 ks. We included data from 3 to 30 keV in all time bins. Our base model consisted of a power law with a fixed Galactic absorption column of 8.09 × 10^{20} cm^{-2} (Kalberla et al. 2005), an additional cold absorber with a free column density, and an Fe line modeled with a Gaussian. Results from this fitting are shown in Figure 2 and example spectra with models and best-fit residuals are shown in Figure 3. Reduced χ² values were close to 1 in all cases.

It is clear that N_H increased significantly for ~6 months between 2010 August and 2011 February, rising from ~20 \times 10^{22} \text{ cm}^{-2} to a maximum of 27 \times 10^{22} \text{ cm}^{-2}. The average column density in the 7 months preceding this event was 20.9 \times 10^{22} \text{ cm}^{-2}. The photon index values were consistent with a constant \Gamma = 1.87 \pm 0.03 through this 16 month period. Fe line parameters (which are not shown here) were poorly constrained but showed no evidence for strong variability. We tried applying the \textsc{cabs} model to test whether the slight fluctuations in the unabsorbed 2–10 keV flux were due to extra scattering by the increased amount of material in the line of sight. This model is more commonly used for Compton-thick sources to model the attenuation of the power law by scattering, however, since the changes in N_H were less than 10^{23} \text{ cm}^{-2}, including this model did not affect the relative magnitude of the fluctuations and we did not use it in our final analysis.

Figure 2. Time-resolved spectral fitting parameters from 2010 January through 2011 April. The top panel shows the column density along with a dotted line indicating the average value for the first 200 days of 20.8 \times 10^{22} \text{ cm}^{-2}. The middle panel shows the unabsorbed 2–10 keV flux, and the bottom panel the photon index, both with dotted lines indicating the average values for each. Note that the photon index is consistent with maintaining a constant value of 1.87 \pm 0.03 throughout the monitoring.
We tested three density profiles for the increase in $N_H$ above a constant baseline which was left free: a sphere of uniform density; a $\beta$ profile as used by Lamer et al. (2003) to fit a similar occultation observed in NGC 3227 given by the equation

$$N_H(r) = N_{H,\text{center}} \times \sqrt{1 - (r/R_c)^2},$$

where $R_c$ is the core radius (Dapp & Basu 2009); and a linear-density sphere with a maximum central density and a density profile described by the equation

$$\rho(r) = \rho_{\text{center}} \times \frac{(R - r)}{R},$$

where $R$ is the outer radius of the spherical clump. Figure 4 shows the data, models, and fit residuals for all three models. The linear-density sphere gave the best fit with $\chi^2$/dof = 73/43. The $\beta$ model gave $\chi^2$/dof = 96/43 and the uniform sphere gave an unacceptable fit with $\chi^2$/dof = 160/43. For the linear-density sphere we found that the occultation lasted a total of 170 days with a maximum column density of $8.4 \times 10^{22}$ cm$^{-2}$ above a baseline of $20.9 \times 10^{22}$ cm$^{-2}$. The core radius crossing time (FWHM) for the $\beta$ model was 60 days with a maximum column density of $10.3 \times 10^{22}$ cm$^{-2}$ above a constant baseline level of absorption of $19.0 \times 10^{22}$ cm$^{-2}$. For analysis of the physical attributes of the clump based on these models see Section 3.

We also tested for cometary tails as seen by Maiolino et al. (2010), testing for asymmetry in the ingress and egress durations, however, these did not improve the fit. From visual inspection it is clear that the Cen A occultation is fairly symmetrical with a smooth, gradual increase and decrease in the column density whereas a comet-like shape would be appropriate for a rapid increase and slow decrease. Consequently, this model is inappropriate for this source.

3. DISCUSSION

Of the other AGNs with similar short-term increases or decreases in $N_H$, many have posited that these clouds are part of the BLR rather than constituents of the torus. The low density of the clumps observed in Cen A combined with the lack of detected broad lines in this source (Alexander et al. 1999) make this a very unlikely scenario. Therefore, we conclude that the transiting clump(s) that have been seen in this source must arise from the dusty torus.

The clumpy torus model of Nenkova (Nenkova et al. 2008a, 2008b) predicts a small number of clumps along the line of sight to the nucleus making up the total observed column density. This is borne out in our observation. The ratio of the baseline column density to the average increase caused by the clump is $\sim$5. We can therefore assume that the number of clouds along the line of sight is $\lesssim 5$ since some of the baseline absorption column may be dust free and reside inside the inner radius of the dusty torus. For example, the very short transits seen by Risaliti et al. (2009) must come from inside the dust sublimation radius. Assuming a viewing angle to the equatorial plane of $62^\circ$ and an angular distribution of clouds of $60^\circ$ (Ramos Almeida et al. 2009) we calculate that the average number of clouds along an equatorial ray is $\lesssim 14$. This is consistent with Rothschild et al. (2011) as well as the predicted number of clumps from Nenkova et al. (2008b) which is no more than 10–15 clumps along an equatorial ray.
Assuming that all of these clouds have an average column density of $4 \times 10^{22}$ cm$^{-2}$ this would imply a total column density along the equator of $\sim 6 \times 10^{23}$ cm$^{-2}$ which is just on the verge of being Compton-thick. This is reasonable given that no Compton reflection signal has ever been detected in this source.

The distance of the dusty torus in Cen A from the central illuminating source derived from infrared measurements by Meisenheimer et al. (2007) was 0.1–0.3 pc. For a bolometric luminosity of $10^{43}$ erg s$^{-1}$ (Whysong & Antonucci 2004), Nenkova et al. (2008b) calculated an inner dust sublimation radius of 0.04 pc. We can place limits on the radius of the torus by following the calculations of Lamer et al. (2003) which use the information that the obscuring material is completely cold with an ionization parameter $\lesssim 1$ and assuming Keplerian motion. Their Equation (3) gives a relationship between the radius of the material and the ionizing luminosity ($L_{\text{ion}}$) of the source:

$$R \simeq 4 \times 10^{16} \frac{M_{\text{BH}}^{1/3}}{L_{\text{ion}}^{2/3}} \left( \frac{L_{\text{ion}}}{N_{22} \xi} \right),$$  \hspace{1cm} (3)$$

where $M_{\text{BH}}$ is the mass of the black hole which has been measured at $M_{\text{BH}} = 6 \times 10^7$ $M_\odot$ (Cappellari et al. 2009; Neumayer et al. 2010), $L_{\text{ion}} = L_{\text{ion}}/10^{42}$ where $L_{\text{ion}} \approx 3 \times 10^{42}$ erg s$^{-1}$ is the ionizing radiation at 13.6 keV, $t_{\text{days}}$ is the crossing time of the event, and $N_{22}$ is the maximum column density of the clump. Assuming $\xi = 1$ cm s$^{-1}$ gives a minimum distance to the torus of $\sim 0.1$ pc, consistent with the values found from infrared measurements. We adopt an inner radius of 0.1 pc and an outer radius of 0.3 pc.

Using parameters determined by the linear-density sphere model (this model gives a better fit to the data than the other models, though it is a purely empirical model), we can calculate the size of the clump and quantify the density profile. To begin we adopted the assumptions made in Rothschild et al. (2011) for Keplerian motion at 0.1–0.3 pc around the $6 \times 10^7 M_\odot$ black hole and calculated a clump velocity of $\sim 930$–1600 km s$^{-1}$. Combining this with the measured 170 day transit we found a linear-density sphere with a diameter of $(1.4–2.4) \times 10^{15}$ cm with a central number density of $n_{\text{H}} = (1.8–3.0) \times 10^7$ cm$^{-3}$. The total mass of this clump can be approximated as $(2–5) \times 10^{22}$ g or about 3–10 times the mass of the Earth.

For comparison, the occultation (if indeed it was a single absorption event) inferred by Rothschild et al. (2011) lasted between one and four years with an increase in column density of $\sim 6 \times 10^{22}$ cm$^{-2}$. Assuming a single uniform sphere, it was found that the clump would have an inferred length of $(3–12) \times 10^{15}$ cm and a number density of $(1–3) \times 10^7$ cm$^{-3}$.

Fitting this occultation event with a single linear-density sphere model, we found a length of $7 \times 10^{15}$ cm and a central density of $8 \times 10^6$ cm$^{-3}$. The best-fit model with residuals is shown in Figure 5; note that with only three data points we needed to assume the baseline column density rather than leave it as a free parameter as we did with the more recent event. For this baseline we have chosen the long-term average value given in Rivers et al. (2011) of $16.9 \times 10^{22}$ cm$^{-2}$. This is somewhat larger and more diffuse than the more recent clump by a factor of two to three, however, this can easily be explained by inherent variation in clump sizes within the torus. Alternatively two or three much smaller, more dense clumps could adequately fit these three data points with similar characteristics to the more recent event, however, with so few data points it is impossible to place constraints on such a scenario.

One alternative to our hypothesis that a clump of material passed through our line of sight is that soft X-ray emission from the Cen A’s radio jets is contributing to the spectrum below $\sim 5$ keV. Evans et al. (2004) presented this possibility based on observations with Chandra and XMM-Newton, modeling the soft emission as a second power law ($\Gamma = 2$) with a second absorber ($N_{\text{H}} = 3.6 \times 10^{22}$ cm$^{-2}$). If the soft X-rays are indeed from the jets and not scattered/leaked emission from the primary source (Turner et al. 1997), then it is possible to model the change in hardness ratio as a decrease in the soft power law rather than an increase in $N_{\text{H}}$. However, since we are not sensitive below 3 keV we cannot place constraints on such a scenario. Further monitoring with soft X-ray capabilities should break this degeneracy easily since if the emission is leaked there should be a strong correlation between the soft and hard X-ray fluxes.

In conclusion, we have taken advantage of sustained monitoring by RXTE to observe an occultation event in Cen A in detail from ingress to egress. A discrete clump of material likely associated with a clumpy torus transited the line of sight to the central illuminating source for 170 days between 2010 August and 2011 February with a maximum increase in $N_{\text{H}}$ of $8.4 \times 10^{22}$ cm$^{-2}$. Assuming the clump of material was roughly spherical with a linear-density profile and assuming a distance from the central nucleus of 0.1–0.3 pc we found that the clump had a linear dimension of $(1.4–2.4) \times 10^{15}$ cm with a central number density of $n_{\text{H}} = (1.8–3.0) \times 10^7$ cm$^{-3}$, in good agreement with previous results. Two occultation events seen in $\sim 10$ years confirm that clumps of material are indeed transiting our line of sight and evidence suggests that they are part of a clumpy, Compton-thin torus, the characteristics of which are consistent with the model proposed by Nenkova et al. (2008a, 2008b).
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REFERENCES

Alexander, D. M., Hough, J. H., Young, S., et al. 1999, MNRAS, 303, 17
Cappellari, M., Neumayer, N., Reunanen, J., et al. 2009, MNRAS, 394, 660
Dapp, W. B., & Basu, S. 2009, MNRAS, 395, 1092
Evans, D. A., Kraft, R. P., Worrall, D. M., et al. 2004, ApJ, 612, 786
Guainazzi, M., Nicastro, F., Fiore, F., et al. 1998, MNRAS, 301, 1
Jahoda, K., Markwardt, C. B., Radeva, Y., et al. 2006, ApJS, 163, 401
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Lamer, G., Uttley, P., & McHardy, I. M. 2003, MNRAS, 342, L41
Maiolino, R., Risaliti, G., Salvati, M., et al. 2010, A&A, 517, 47
Markowitz, A., Edelson, R., Vaughan, S., et al. 2003, ApJ, 593, 96
McKernan, B., & Yaqoob, T. 1998, ApJ, 501, L29
Meisenheimer, K., Tristram, K. R. W., Jaffe, W., et al. 2007, A&A, 471, 453
Nenkova, M., Sirocky, M. M., Ivezić, Ž., & Elitzur, M. 2008a, ApJ, 685, 147
Nenkova, M., Sirocky, M. M., Nikutta, R., Ivezić, Ž., & Elitzur, M. 2008b, ApJ, 685, 160
Neumayer, N., Cappellari, M., van der Walt, P., et al. 2010, Messenger, 139, 36
Ramos Almeida, C., Levenson, N. A., Rodríguez Espinosa, J. M., et al. 2009, ApJ, 702, 1127
Risaliti, G., Salvati, M., Elvis, M., et al. 2009, MNRAS, 393, L1
Rivers, E., Markowitz, A., & Rothschild, R. E. 2011, ApJS, 193, 3
Rothschild, R. E., Markowitz, A., Rivers, E., et al. 2011, ApJ, 733, 23
Turner, T. J., George, I. M., Mushotzky, R. F., & Nandra, K. 1997, ApJ, 475, 118
Turner, T. J., Reeves, J. N., Kraemer, S. B., & Miller, L. 2008, A&A, 483, 161
Vaughan, S., & Edelson, R. 2001, ApJ, 548, 694
Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, ApJS, 465, 487
Whysong, D., & Antonucci, R. 2004, ApJ, 602, 116
Wilm, J., Allen, A., & McCray, M. 2000, ApJ, 542, 914