RESOLVING THE BONDI ACCRETION FLOW TOWARD THE SUPERMASSIVE BLACK HOLE OF NGC 3115 WITH CHANDRA

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ABSTRACT

Gas undergoing Bondi accretion onto a supermassive black hole (SMBH) becomes hotter toward smaller radii. We searched for this signature with a Chandra observation of the hot gas in NGC 3115, which optical observations show has a very massive SMBH. Our analysis suggests that we are resolving, for the first time, the accretion flow within the Bondi radius of an SMBH. We show that the temperature is rising toward the galaxy center as expected in all accretion models in which the black hole is gravitationally capturing the ambient gas. There is no hard central point source that could cause such an apparent rise in temperature. The data support that the Bondi radius is at about 4′′–5′′ (188–235 pc), suggesting an SMBH of $2 \times 10^9 M_\odot$ that is consistent with the upper end of the optical results. The density profile within the Bondi radius has a power-law index of 1.03±0.23, which is consistent with gas in transition from the ambient medium and the accretion flow. The accretion rate at the Bondi radius is determined to be $M_B = 2.2 \times 10^{-2} M_\odot$ yr$^{-1}$. Thus, the accretion luminosity with 10% radiative efficiency at the Bondi radius ($10^{44}$ erg s$^{-1}$) is about six orders of magnitude higher than the upper limit of the X-ray luminosity of the nucleus.

Key words: accretion, accretion disks – black hole physics – galaxies: elliptical and lenticular, cD – galaxies: individual (NGC 3115) – galaxies: nuclei – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Understanding accretion onto black holes remains one of the most active areas of research in astrophysics today, both for probing black hole properties and because of their impact on larger-scale problems in galaxy and structure formation. In many nearby galaxies, the model of a central black hole gravitationally capturing ambient gas (Bondi accretion; Bondi 1952) is a vital part of our understanding of how black holes are accreting.

The key to understanding the dynamics of gas in the systems of interest lies in correctly modeling the behavior of the accreting gas once it falls within the gravitational influence of the black hole, the Bondi radius $R_B = 2 G M_{BH}/c_s^2$, where $M_{BH}$ is the mass of the black hole and $c_s$ is the sound speed of the gas in the vicinity of $R_B$. In the absence of angular momentum, the black hole is predicted to gravitationally capture the ambient gas (Bondi accretion; Bondi 1952) is a vital part of our understanding of how black holes are accreting.

The very weak radiation from most nearby massive black holes has prompted a significant theoretical effort aimed at explaining the very low radiative efficiencies and/or accretion rates. The central idea is that accretion proceeds via a hot radiatively inefficient accretion flow (RIAF) rather than a canonical thin accretion disk. Early RIAF models include the advection-dominated accretion flow (ADAF; Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994), the convection-dominated accretion flow (CDAF; Narayan et al. 2000; Quataert & Gruzinov 2000), and the advection-dominated inflow–outflow solution (ADIOS; Blandford & Begelman 1999).

Determining which (if any) of these scenarios describes low-$L_X$ black hole systems is of fundamental importance to our understanding of accretion physics and black hole demography. Observational work has focused on using spatially unresolved spectral information to constrain theoretical models. While such studies have been successful in ruling out classical ADAF models in some instances (e.g., Sgr A*; Di Matteo et al. 2001; Baganoff et al. 2003), the main limitation has been the inability of even Chandra to resolve the accretion flow inside $R_B$ and directly determine the density profiles of the accretion flow, as it is the shape of the density profile that most strongly distinguishes the theoretical models. While ADAFs, CDAFs, and ADIOS models all predict that the compression of gas within the accretion flow within the Bondi radius leads to a $T(R) \propto R^{-1}$ relation for the gas, the models predicted significantly different radial density profiles (Section 5).

In this Letter, we present for the first time spatially resolved temperature and density profiles within the Bondi radius of a supermassive black hole (SMBH). Dynamical modeling of the stellar kinematics of the bulge of NGC 3115 has confirmed that it harbors a ($1–2 \times 10^9 M_\odot$) black hole (Kormendy et al. 1996; Emsellem et al. 1999). At a distance of 9.7 Mpc (Tonry et al. 2001), this makes NGC 3115 the nearest $>10^9 M_\odot$ black hole. Despite its large mass, the black hole is very radio quiet, with a core 5 GHz luminosity of less than $4 \times 10^{23}$ erg s$^{-1}$ Hz$^{-1}$ (Franceschini et al. 1998), several orders of magnitude lower than other black holes of similar mass. The black hole is also undetected in X-rays, with a Chandra upper limit of less than $10^{38}$ erg s$^{-1}$ (Diehl & Statler 2008; K.-W. Wong et al. 2011, in preparation). The estimated Bondi accretion rate based on the
previous observed density of \( \approx 0.1 \text{ cm}^{-3} \) (David et al. 2006) in the central part of the galaxy is \( \sim 0.1 \text{ M}_\odot \text{ yr}^{-1} \), implying an expected luminosity \( \sim 10^{43} \text{ erg s}^{-1} \) if accretion occurred with 10% efficiency. The lack of radio power argues that it is unlikely that jets are interacting strongly with the gas inside \( R_B \).

2. X-RAY OBSERVATIONS AND SPECTRAL ANALYSIS

NGC 3115 (Figure 1) was observed with Chandra on 2001 June 14, 2010 January 27, and 2010 January 29 for 37, 41, and 77 ks, respectively. All the data were reprocessed using the Chandra Interactive Analysis of Observations (CIAO) software version 4.3 and the Chandra Calibration Database (CALDB) version 4.4.1. We used a local background that is extracted from the 70′′–90′′ annulus centered at the X-ray peak. The background region is far enough from the center so that the source-removed surface brightness of the X-ray emission is basically flat beyond 70′′. The background only contributes less than about 1% of the total count rate. However, further analysis shows that a modeled circular Gaussian width of this peak emission is twice extended as that of a nearby bright point source and that the central source is static (varied less than 2σ) within and between the observations. Thus, it is dominated by a concentration of hot gas and unresolved binaries rather than a single compact accreting object. We included this peak emission but excluded all the other sources detected by wavdetect during the analysis.

We extracted spectra in annuli centered at the central peak of the extended X-ray emission. This peak was detected as a source by CIAO wavdetect. However, further analysis shows that a modeled circular Gaussian width of this peak emission is twice extended as that of a nearby bright point source and that the central source is static (varied less than 2σ) within and between the observations. Thus, it is dominated by a concentration of hot gas and unresolved binaries rather than a single compact accreting object. We included this peak emission but excluded all the other sources detected by wavdetect during the analysis.

The unresolved X-ray emission is mainly contributed by unresolved low-mass X-ray binaries (LMXBs), cataclysmic variables and coronally active binaries (CV/ABs), and the diffuse hot gas component that we are interested in. The very soft emission from the gas and the very hard emission from the unresolved LMXBs are easy to separate spectrally. No appreciable emission is expected from the gas above 2 keV, so we can use the 2–6 keV emission as a lever arm for estimating the amount of unresolved LMXB flux in the 0.5–2 keV band and subtract it accordingly if we assume an appropriate spectral model for the LMXBs. Irwin et al. (2003) have shown that the summed spectra of resolved low-LX \( (< 10^{37} \text{ erg s}^{-1}) \) LMXBs in the bulge of M31 are very similar to more luminous LMXBs. Hence, it is valid to assume that the unresolved LMXB emission can be spectrally modeled as the brighter resolved sources. We found that the fainter, softer source like those that make up the Galactic Ridge emission (CV/AB) contributes similarly to the soft flux of the gas based on \( L_X \sim L_K \) scaling relations within 4′′ for this component, where \( L_K \) is the Two Micron All Sky Survey \((2MASS) K\)-band luminosity. Hence, including this component is essential in the analysis.

For the LMXB component, we take \( \Gamma_{\text{LMXB}} = 1.61^{+0.02}_{-0.02} \) measured from the combined spectrum of all the resolved point sources within \( D_{25} \) of NGC 3115. For the CV/AB component, we fitted the unresolved X-ray emission of M32, which is believed to be truly gas free (Revnivtsev et al. 2007; Boroson et al. 2011), using an absorbed thermal + power-law model. The best-fit temperature is \( T_{\text{CV/AB}} = 0.59^{+0.05}_{-0.13} \) keV and the power-law index is \( \Gamma_{\text{CV/AB}} = 1.93^{+0.09}_{-0.09} \), which are consistent with the values measured by Revnivtsev et al. (2008). The CV/AB normalizations of each annulus are determined by the \( L_X-L_K \) scaling relation derived from M32.

We used the X-ray Spectral Fitting Package\(^4\) (XSPEC) for spectral analysis. The 2001 and 2010 spectra of each annulus in the 0.5–6.0 keV energy range were fitted jointly to the three-component absorbed model (PHABS in XSPEC)—a thermal model (APEC in XSPEC) for the gas, a power-law (POWERLAW in XSPEC) for the unresolved LMXBs, and a combination of thermal + power-law (APEC + POWERLAW) model for the CV/ABs. The absorption is fixed at the Galactic value of \( N_H = 4.32 \times 10^{20} \text{ cm}^{-2} \) (Dickey & Lockman 1990). We fit the temperature of the thermal gas component. The normalizations of the thermal gas and the LMXB components are allowed to vary and unti. Since the abundance cannot be constrained from the spectra, we fixed it to solar value. Using 0.2 solar only increases the best-fit temperature by \( \leq 10\% \) and increases the gas normalizations by a factor of four. The derived density only increases by a factor of two and all our conclusions remain the same. All the other parameters are fixed as described above. The spectra were fitted using the \( c \)-statistic. Varying \( \Gamma_{\text{LMXB}} \) or \( \Gamma_{\text{CV/AB}} \) by their 1σ uncertainties or varying the CV/AB normalizations by \( \pm 20\% \) (that is larger than their 1σ uncertainties) only changes the best-fit gas temperature or the gas normalizations by \( \sim 9\% \).

3. TEMPERATURE PROFILE

The projected temperature profile is shown in the upper panel of Figure 2. Although the error bars are quite large, it can be seen that the trend is rising toward the center as expected in a Bondi flow. We have also constructed a physical model with a temperature profile expected in a Bondi flow (i.e., \( T \propto R^{-1} \)) and a density profile taken from our best-fit model \( (\rho(R) \propto R^{-1}; \text{see Section 4 below}) \). The simulated projected temperature profile is consistent with our measured profile. In particular, the simulated projected temperature within the 2″ region is biased

\(^4\) http://heasarc.nasa.gov/xanadu/xspec/
Figure 2. Upper panel: projected temperature profile of the hot gas component. Different colors are with different binnings. Lower panel: deprojected density profile. The best-fit power-law model within 4′ is shown in solid line. (A color version of this figure is available in the online journal.)

Figure 3. Normalized probability (solid line) and the cumulative probability (dotted line) of the simulated temperature ratios between the 2′–4′ (T1) and the 4′–10′ (T2) annuli. The vertical line cuts the cumulative probability at 10%.

low with respect to the deprojected (physical) temperature and is consistent with our measured low value. Thus, the bias in the central temperature may be explained by the projection of the cooler gas from the outer region.

For a measured ISM temperature of 0.3 keV in the outer most bin, this corresponds to Rg = 112–224 pc (2′/4–4′/8) depending on the adopted black hole mass estimate ((1–2) × 109 M⊙). Careful selection of the boundary radius suggests that the onset in the increase in temperature begins at 4′–5″, rather than at 2″. To confirm this, we have performed a Markov chain Monte Carlo (MCMC) simulation to address the significance of the rise in temperature just within a radius of 4″. The distribution (normalized probability) and the cumulative probability of the simulated temperature ratios between the 2″–4″ and the 4″–10″ annuli are plotted in Figure 3. The MCMC test suggests that the temperature ratio is larger than 1.13 at the 90% confidence level. Assuming that the temperature beyond Rg is constant and T ∝ R−1 inside Rg, the expected temperature ratio at 3″ and at Rg (4″) is 1.33, which is consistent with the peak ratio of 1.4 in the MCMC simulation.

5 Note that the temperature profile can be flatter in the transition region between the ambient ISM and the central accretion flow near ∼0.1–1 Rg (Quataert 2002).

The harder spectrum within 4″ is not the spurious result of any hard central point source. We obtained the same overall result even when we excised the inner 1″. The effect of unresolved X-ray binaries has been properly accounted for by quantifying the unresolved emission in the 2.0–6.0 keV band and extrapolating to lower energies. The effect of a large number of softer accreting white dwarfs, stellar coronae, etc., has also been taken into account in our analysis. Such an increase in the temperature is exactly what is expected in all models in which the black hole is gravitationally capturing the ambient gas (see, e.g., Quataert & Narayan 1999; Quataert & Gruzinov 2000). In fact, a similar spike in ISM temperature was found at the center of NGC 4649 and was interpreted as confirmation of a >109 M⊙ black hole (Humphrey et al. 2008), although in this galaxy Rg is unresolved by Chandra. Finally, the lack of detectable radio emission from the core of NGC 3115 argues against heating of the gas from jets.

4. SURFACE BRIGHTNESS AND DENSITY PROFILES

We have calculated the surface brightness profiles for the thermal gas, CV/AB, and LMXB components. The CV/AB profile was calculated using the same Lx–Lx scaling relations mentioned above. The LMXB profile was calculated by assuming that the emission above 2 keV is contributed by the LMXBs only, and its contribution to the soft emission was calculated by the assumed spectral model above. The gas profile in the soft band was calculated by subtracting the CV/AB and LMXB contributions. Figure 4 shows the surface brightness profiles for the three components in the 0.5–1.0 keV energy band. The upper limit is chosen to maximize the contribution from the gas component with respect to the other two components. Note that the gas component is clearly detected within ∼15″ and is rising more steeply compared with the stellar (CV/AB) component toward the center.

With the surface brightness profile for the hot gas component, the electron density profile can be deprojected. We converted the count rate in each annulus into flux using the XSPEC APEC model with a temperature of 0.45 keV and solar abundance. The temperature was taken as the mid value of the best-fit temperature of the central 0″–2″ bin and the ambient temperature. Since the emissivity mainly depends on density, the precise value of temperature is not important at our level of accuracy. We have tested the density profiles derived using different...
temperatures between 0.3–0.6 keV. All the derived density profiles are consistent within the error bars. The flux was then deprojected into emissivity, $\epsilon$, at each radius using a method described in Wong et al. (2008) and also described in Kriss et al. (1983). This technique calculates the emission measures of each spherical shell starting from the outer most annulus toward the center, and the emission measure of each subsequent shell is calculated by subtracting the projected emission from the outer shells. The electron density can then be converted from the emissivity by the relation $\epsilon = n^2 A$, where the emissivity function $A$ depends on the temperature and the abundance. The emissivity function is taken from the same APEC model.

The deprojected electron density profile is shown in the lower panel of Figure 2. The errors were estimated by running $10^6$ Monte Carlo simulations. Fitting the density profile within $4''$ to a power law gives $\rho \propto R^{-0.16^{+0.21}_{-0.23}}$. This is consistent with the power-law index of $1.14^{+0.29}_{-0.28}$ in the $4''$–$25''$ region.

5. DISCUSSION

Accretion models predict that gas within the Bondi radius flows toward the SMBH. The increases in the temperature and density of thermal gas toward the center are direct evidence that the gas is being gravitationally captured by the SMBH. Resolving the temperature and density profiles within the Bondi radius can provide tight constraints to accretion models.

Our 150 ks Chandra observation of NGC 3115 supports that there is a rise in temperature inside $R_B$ compared to the galaxy’s ISM temperature outside $R_S$, exactly as expected from accretion models. We have shown that the onset in the increase in temperature begins at $\approx 4''$–$5''$ rather than at $2''$. This supports that the mass of the SMBH is at the upper end of the $(1-2) \times 10^9 M_\odot$ range (Kormendy et al. 1996; Emsellem et al. 1999).

In previous studies where the Bondi accretion flow could not be spatially resolved, the overall spectrum has to be modeled from the integrated emission across the entire region. In our observations, the emissions from the outer shells are consistent within the error bars. The flux was then deprojected into emissivity, $\epsilon$, at each radius using a method described in Wong et al. (2008) and also described in Kriss et al. (1983). This technique calculates the emission measures of each spherical shell starting from the outer most annulus toward the center, and the emission measure of each subsequent shell is calculated by subtracting the projected emission from the outer shells. The electron density can then be converted from the emissivity by the relation $\epsilon = n^2 A$, where the emissivity function $A$ depends on the temperature and the abundance. The emissivity function is taken from the same APEC model.

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We determined that the Bondi accretion rate of NGC 3115 is $\dot{M}_B = 2.2 \times 10^{-2} M_\odot$ yr$^{-1}$. Assuming a $10%$ radiative efficiency, the accretion luminosity at $R_B (10^{44}$ erg s$^{-1}$) is about six orders of magnitude higher than the upper limit of the X-ray luminosity of the nucleus. Such a discrepancy can be explained if the accretion rate is lower than the classical Bondi rate. For example, the accretion rate for the ADIOS or CDAF models is suppressed and scales with radius as $M_{\text{acc}} \propto \alpha M_B/R_{B}$, where $\alpha$ is the dimensionless viscosity parameter in the standard thin disk model (Shakura & Sunyaev 1973; Baganoff et al. 2003). Using a typical value of $\alpha \approx 0.1$ to calculate $M_{\text{acc}}$ at $R_S$, $\rho$ should be close to 1 to explain the discrepancy. It is also quite possible that the gas has non-negligible angular momentum that should be more important at smaller radii. This can reduce the accretion rate near the event horizon (e.g., Proga & Begelman 2003). Alternatively, the radiation efficiency can be lower than the canonical value of 0.1 (e.g., Ho 2008).

Currently, the uncertainties are limited by the statistics of our data. A deep Chandra observation will improve the statistics to provide useful constraints to accretion models.

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REFERENCES