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VERY BROAD [O III] λλ4959, 5007 EMISSION FROM THE NGC 4472 GLOBULAR CLUSTER RZ 2109 AND IMPLICATIONS FOR THE MASS OF ITS BLACK HOLE X-RAY SOURCE[1]

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ABSTRACT

We present Keck LRIS spectroscopy of the black hole–hosting globular cluster RZ 2109 in the Virgo elliptical galaxy NGC 4472. We find that this object has extraordinarily broad [O III] λ5007 and [O III] λ4959 emission lines, with velocity widths of approximately 2000 km s^{-1}. This result has significant implications for the nature of this accreting black hole system and the mass of the globular cluster black hole. We show that the broad [O III] λ5007 emission must arise from material driven at high velocity from the black hole system. This is because the volume available near the black hole is too small by many orders of magnitude to have enough [O III]-emitting atoms to account for the observed L([O III] λ5007) at high velocities, even if this volume is filled with oxygen at the critical density for [O III] λ5007. The Balmer emission is also weak, indicating the observed [O III] is not due to shocks. We therefore conclude that the [O III] λλ4959, 5007 is produced by photoionization of material driven across the cluster. The only known way to drive significant material at high velocity is for a system accreting mass near or above its Eddington limit, which indicates a stellar-mass black hole. Since it is dynamically implausible to form an accreting stellar-mass black hole system in a globular cluster with an intermediate-mass black hole (IMBH), it appears this massive globular cluster does *not* have an IMBH. We discuss further tests of this conclusion, and its implications for the M_{BH}-$M_{stellar}$ and M_{BH}-σ relations.

Subject headings: galaxies: individual (NGC 4472) — galaxies: star clusters — globular clusters: general — X-rays: binaries — X-rays: galaxies: clusters

1. INTRODUCTION

Maccarone et al. (2007) presented the first unambiguous evidence for a black hole in a globular cluster. This was based on an *XMM* observation of strong variability in a high-luminosity X-ray source ($\simeq 4 \times 10^{39}$ ergs s^{-1}) located in the spectroscopically confirmed globular cluster RZ 2109 in the Virgo elliptical galaxy NGC 4472. The high X-ray luminosity, about an order of magnitude greater than the Eddington luminosity of a neutron star, requires either a black hole or multiple neutron stars in the old stellar population of the globular cluster. The strong variability rules out multiple neutron stars as the source of the bright X-ray emission, and thus indicates the globular cluster RZ 2019 hosts a black hole X-ray source.

Subsequently, Zepf et al. (2007, hereafter Z07) discovered broad [O III] λ5007 emission from this black hole–hosting globular cluster. Specifically, Z07 analyzed existing VLT spectra of this object covering a wavelength range of 5000–5800 Å. They identified a broad emission line in these data at a wavelength in very close agreement (within 10 km s^{-1}) with that expected for [O III] λ5007 at the radial velocity of the globular cluster previously determined from its stellar absorption lines. Z07 also found that the [O III] λ5007 emission line was much broader than any possible velocity dispersion for the globular cluster, with an estimated width of several hundred km s^{-1}, and the possibility of much broader wings in the data. They noted such a large velocity width clearly points to the black hole as the source of the power driving the nebular emission.

As described in Z07, understanding how the broad [O III] λ5007 emission is produced provides a way to constrain the mass of the black hole in this globular cluster. One possibility is that the black hole is a stellar-mass system, accreting near or above its Eddington limit. Such systems can drive strong, high-velocity winds (Begelman et al. 2006 and references therein). In this case, broad [O III] could be produced either by shocks as the wind passes through the globular cluster's interstellar medium, or by photoionization of this wind material across the cluster. Alternatively, it could be an intermediate-mass black hole, in which case it would be far below its Eddington luminosity given the observed X-ray luminosity. In this case, no strong winds would be driven, and any broad [O III] emission would have to be produced by photoionizing of material in very close proximity to the black hole.

The X-ray data alone do not clearly distinguish between these possibilities. There are also a wide range of theoretical predictions for the fate and properties of black holes in globular clusters. For example, extrapolations of the M_{BH}-σ and M_{BH}-$M_{stellar}$ relations tend to predict IMBHs in globular clusters (see § 4), and some models find sufficiently dense young globular clusters cores may experience runaway stellar mergers that may form IMBHs (e.g., Portegies Zwart & McMillan 2002; Freitag et al. 2006; but see also Yungelson et al. 2008). On the other hand, as stellar-mass black holes sink to the centers of globular clusters through mass segregation, dynamical in-

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teractions between them may eject most or all of the black holes from the core, either into the outskirts of the globular cluster (Mackey et al. 2008), or out of the cluster completely (e.g., Sigurdsson & Hernquist 1993; Kulkarni et al. 1993).

In this Letter , we present new optical spectroscopy aimed at understanding the physical nature of the accreting black hole source in the globular cluster RZ 2109. The optical spectra used in Z07 were available because of an ongoing kinematic study of the NGC 4472 globular cluster system using FLAMES, a multifiber spectrograph on the VLT. The FLAMES spectra have very limited wavelength coverage and a modest signal-to-noise ratio. The work presented here both significantly increases the wavelength coverage to investigate diagnostic line ratios, and improves the signal-to-noise ratio to better constrain the width of the broad [O III] λ5007 emission line.

2. OBSERVATIONS

We obtained optical spectra of the NGC 4472 globular cluster RZ 2019, which contains the X-ray source XMMU 1229397+07533, on UT 2007 December 17–18 with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the Keck I telescope. The observations, taken at a position angle of 74.4°, through a 1.5″ slit, used the D560 dichroic, the 400 line mm^{-1} grism (λ_{blaze} = 3400 Å) on the blue side, and the 400 line mm^{-1} grating (λ_{blaze} = 8500 Å) on the red side. The spectral resolution for objects filling the slit was $R \sim$ 400 and 700 on the blue and red sides, respectively. The nights were not photometric, and the seeing ranged from moderate (1.2″; first night) to poor (1.6″; second night). The exposure times were 1500 s each night.

Data processing followed standard slit spectroscopy procedures. In particular, we extracted the spectra using a 1.5″ wide aperture and calculated the spectral dispersions using lamp spectra obtained earlier in the nights, adjusting the wavelength zero point based on telluric emission lines. The spectra were flux calibrated using observations of standard stars from Massey & Gronwall (1990) obtained during the same nights. Since the nights were not photometric, the spectra were scaled to match the observed optical brightness of RZ 2109 (V = 21.0). We also corrected the atmospheric A and B band bands based on the standard star spectra. The final, calibrated spectrum is shown in Figure 1.

3. RESULTS

In this Letter, we focus on two key aspects of the remarkable spectrum of RZ 2109 shown in Figure 1. These are (1) the very broad velocity width of the [O III] λλ4959, 5007, and (2) the [O III] λ5007 line luminosity and the large ratio of the [O III] λ5007 to Hβ. We also note that this spectrum clearly shows [O III] λ5007, [O III] λ4959, and likely [O III] λ4363 in emission at the radial velocity of the globular cluster previously determined from its stellar absorption lines. This confirms beyond any doubt that these emission lines are from the globular cluster RZ 2109, as found by Z07 from the [O III] λ5007 line alone.

3.1. *The Extraordinary* [O III] λλ4959, 5007 *Velocity Width*

The spectrum in Figure 1 shows that the [O III] λ4959 and λ5007 emission lines are extremely broad, so broad that the lines are blended. To determine the velocity width of these lines we first use standard deblending procedures. Specifically, we fit the two lines with two Gaussians, keeping the width of the lines the same because they come from the same initial atomic state. This

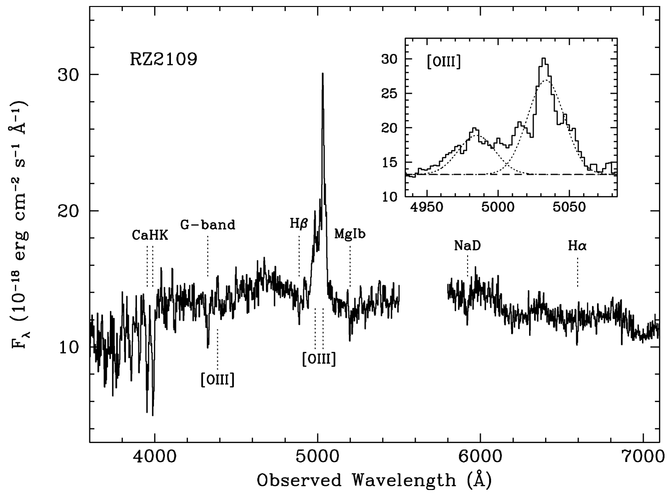

FIG. 1.—Plot of F_λ vs. λ for RZ 2109, the NGC 4472 globular cluster in which the black hole system XMMU 1229397+075333 is found. This figure shows the remarkably strong and broad [O III] λλ4959, 5007 emission lines. The inset figure shows the [O III] λλ4959, 5007 region in more detail. The light dashed lines on the inset figure are the Gaussian fits to the [O III] λλ4959, 5007 lines, with a FWHM of 2000 km s^{-1}. This demonstrates the extraordinary width of these lines. This Letter focuses on these lines and the implication of their luminosity and velocity width. There also appears to be velocity structure beyond the individual Gaussian fits, but higher spectral resolution than the $R \simeq 400$ of these data is needed for a reliable assessment of structure within the very broad lines. The gap around 5600 Å is due to the dichroic in the LRIS spectrograph. The stellar absorption lines are from the stellar population of the host globular cluster, with some likely filling in of the Balmer lines due to weak Balmer emission, as discussed in the text.

gives a FWHM of the lines of 33 Å, corresponding to a velocity FWHM of approximately 2000 km s^{-1}.

Figure 1 shows the lines have stronger central peaks and broader wings than the best-fitting Gaussian functions. We therefore also calculate the velocity width of the lines by determining the longest wavelength at which the [O III] λ5007 line clearly has significant flux. We determine the corresponding shortest wavelength for the [O III] λ4959 line to estimate the lowest velocity component. Using this technique, we find a velocity extent of the emission of at least +1600 and −1400 km s^{-1}. Whether the [O III] λλ4959, 5007 lines are described as having FWHM of 33 Å, or having a velocity extent of at least ±1500 km s^{-1}, these lines are extraordinarily broad, as broad as almost any [O III] λ5007 lines observed, while being located in a globular cluster with an estimated mass of a few million solar masses and an escape velocity several orders of magnitude less than the observed velocity width.

3.2. *Line Luminosities and Ratios*

The [O III] λ5007 line luminosity and its comparison to other diagnostic lines such as Hβ place important constraints on the nature of the accreting black hole system. One way to calculate L([O III] λ5007) is to use the Gaussian fits to the [O III] lines described above. These give fluxes of 1.8×10^{-16} and 4.4×10^{-16} ergs s^{-1} cm^{-2} for [O III] λ4949 and [O III] λ5007, respectively. Adopting a 16 Mpc distance for NGC 4472 then gives a line luminosity of L([O III] λ5007) = 1.4×10^{37} ergs s^{-1}.

An alternative approach to determining the [O III] λ5007 luminosity that avoids Gaussian fitting is to determine the total [O III] λ4959 + λ5007 luminosity, and adopt the 3 to 1 ratio of L([O III] λ5007) to L([O III] λ4959) given by atomic physics (e.g., Dimitrijević et al. 2007; Storey & Zeippen 2000). We do this by measuring the straightforward equivalent width and total [O III] λ4959 + λ5007 flux, and then using the above ratio between the lines to determine L([O III] λ5007). This calculation gives an [O III] λ5007 equivalent width of 31 Å, and L([O III] λ5007) $= 1.4 \times 10^{37}$ ergs s^{-1}. While the close agreement of this determination with that above is undoubtedly partially fortuitous, it is also reassuring that different techniques for determining the line luminosities give similar answers. We also note that the L([O III] λ5007) found here is significantly higher than the best estimate in Z07. Z07 noted that the line might have broad wings, and that if the broad wings were real, their velocity width and L([O III] λ5007) estimates would be lower limits.

The [O III] λ5007 to Hβ ratio is a valuable diagnostic emission line mechanism. It is immediately apparent from Figure 1 that the Balmer line emission is not strong; the Balmer lines are all seen in absorption. Balmer absorption lines are expected from the stellar population of the globular cluster. The Hβ emission can be estimated by comparing the amount of Hβ absorption expected from stellar population models to that observed, attributing any difference to filling in of the stellar absorption line by Hβ emission from the black hole system. To carry out this measurement, we use the stellar populations models of Bruzual & Charlot (2003), and those of A. Vazdekis et al. (2008, in preparation) based on the spectral library of Sánchez-Blázquez et al. (2006), since these provide spectra at fairly high resolution. For each set of models, we adopt an age of 12 Gyr and set the model metallicity to match the observed optical colors of RZ 2019. We then analyze the spectral output of the models in the same way as the data. Both models predict an equivalent width of 2.6 Å for the Hβ absorption line, while the same measurement of the observed spectrum gives 1.5 Å.

Our analysis therefore suggests an Hβ equivalent width of about 1.1 Å giving a very rough L[O III] λ5007/L[Hβ] ratio of 30. We caution that this is somewhat dependent on the stellar population modeling of the stellar Balmer absorption. There are also hints in the current data that the Balmer emission may not be as broad as the [O III] λλ4959, 5007 lines, and we plan to address this and other questions about the detailed shape of the [O III] λλ4959, 5007 line complex in future work with higher spectral resolution. We will address this further in a future paper. Here we simply note that the [O III] λ5007/Hβ ratio appears to be large.

4. DISCUSSION

Zepf et al. (2007) noted three possibilities for producing the broad [O III] λ5007 emission. One is that it could be produced by shocks from a strong, high-velocity wind driven from a black hole. Driving such winds requires a system undergoing mass transfer at or above its Eddington limit, which given the observed $L_X \simeq 4 \times 10^{39}$ ergs s^{-1} would indicate a stellar-mass black hole system of $M_{BH} \simeq 10\ M_\odot$. Alternatively, the velocity width could be generated by a strong wind driven across the globular cluster, but the ionization source could be photoionization from the powerful central system. Because this case involves strong winds, it too implicates a stellar-mass black hole system. The third possibility is that the high velocities are due to gravitational motions very close to the central black hole, and the material is photoionized. This scenario likely implicates an IMBH to more readily give the high velocities at sufficient distances to allow [O III] emission.

The new results presented here—the very broad [O III] λ4959 and λ5007 emission lines extending over more than 1000 km s^{-1}, and the large [O III] λ5007/Hβ ratio—strongly constrain these possibilities. First, the large [O III]/Hβ ratio indicates the [O III] λ5007 is not produced directly by shocks. Second, the large line widths extending to high velocities rule out the idea the velocity widths seen in the [O III] λλ4959, 5007 lines can be due to gravitational motions very near a black hole. This is because the volume available near the black hole where the line widths would be as large as observed is too small by orders of magnitude to have enough [O III] emitting atoms.

To calculate the maximum possible [O III]λ5007 flux for material orbiting around a black hole, we first find the volume available in a shell corresponding to a given circular velocity around the black hole. We then determine the maximum possible [O III]λ5007 flux at this velocity by assuming this volume is filled completely with material at the critical density of [O III] λ5007 with a solar O/H ratio, and taking the collisional excitation rate for [O III] λ5007 (Osterbrock & Ferland 2006). We find that the maximum flux for material with a velocity of 1500 km s^{-1} around a 1000 $M_\odot$ black hole is F_λ([O III] λ5007) $= 8 \times 10^{-26}$ ergs s^{-1} cm^{-2} $Å^{-1}$. This is the maximal flux in that it assumes the entire available volume is at the critical density of [O III] λ5007, that all the O atoms are doubly ionized, and that the O/H ratio is solar, while the best estimate for the metallicity of RZ 2109 is about 1/50 $Z_\odot$ (Maccarone et al. 2007; Rhode & Zepf 2001). In contrast to this maximum flux from material orbiting around a black hole, the observed F_λ([O III] λ5007) at velocities around 1500 km s^{-1} is somewhat larger than 10^{-18} ergs s^{-1} cm^{-2} $Å^{-1}$ (see Fig. 1), or more than 10^7 times greater. Thus, even the maximal emission from material orbiting around a black hole fails by many orders of magnitude to match the flux in the observed broad [O III] λ5007 line. One can increase the flux by assuming an even higher O abundance, or by increasing the available volume by going to higher M_{BH} or lower velocity. However, the difference is so great and the presence of significant flux at large velocities so clearly observed that these do not begin to reconcile this scenario with the observations.

Therefore, the only scenario consistent with the data is that in which the black hole system drives material across the cluster, and that this material is also photoionized by the central X-ray source. Such a scenario strongly implies that the black hole is a stellar-mass black hole and not an IMBH, based on both theoretical and observational considerations. Extensive theoretical work has found that strong winds like those found here are driven only by systems with mass accretion rates similar to or larger than the Eddington limit (e.g., Proga 2007 and references therein). Given the observed X-ray luminosity of 4×10^{39} ergs s^{-1}, this strongly implies a stellar-mass black hole, with a mass of $M_{BH} \simeq 10\ M_\odot$ giving a good fit to the X-ray data in this scenario (Maccarone et al. 2007).

A stellar mass for the accreting black hole system in RZ 2109 is also supported by the high L/L_{Edd} found for the small fraction of extragalactic AGNs with observed broad velocity widths in [O III]λ5007. One well-studied example is NGC 1068, which has long been known to have highly blueshifted [O III] λ5007 components with the emission dominated by photoionization (Groves et al. 2004; Kinkhabwala et al. 2002), and for which the central source appears to be above its formal Eddington limit (e.g., Bock et al. 2000). A small fraction of narrow-line Seyfert 1 galaxies are also observed to have either an underlying broad or significantly blueshifted [O III] λ5007 component, which is found to be related to high L/L_{Edd} ratios (e.g., Komossa et al. 2008; Boroson 2005), further suggesting RZ 2109 is near its Eddington luminosity.

Thus, theory and observation indicate that the black hole in this globular cluster system is very likely a stellar-mass black hole. As discussed in Z07, it seems highly unlikely that a close, accreting black hole binary system could form in a globular cluster with an IMBH at its center. This is because the dynamical processes by which close black hole X-ray binaries form in globular clusters happen in their cores, but dynamically, a globular cluster core containing an IMBH will have typically ejected its stellar-mass black holes (see Z07 for full discussion).

The globular cluster RZ 2109 appears to have only stellar-mass black hole(s), with no intermediate mass black hole. As such it falls far off the relations between black hole mass and the mass and velocity dispersion of the stellar system in which it is found. To show this explicitly, we first calculate the M_{BH} for RZ 2109 implied by the M_{BH}-$M_{stellar}$ relation found by Häring & Rix (2004). For the stellar mass of RZ 2109, we use its absolute luminosity of $M_V = -10$, and a $(M/L)_V = 2$ standard for globular clusters to estimate a stellar mass of about $2 \times 10^6\ M_\odot$. Based on the Häring & Rix (2004) relation, a M_{BH} of 900 $M_\odot$ would be predicted for RZ 2109, with an uncertainty of a factor of 2. This is far greater than the stellar mass of ~10 $M_\odot$ indicated by the calculations above. Extrapolating the M_{BH}-σ relation to RZ 2109 tends to predict even larger black hole masses than the M_{BH}-$M_{stellar}$ relation. A direct determination of the σ of RZ 2109 is not feasible, but we can compare it to the σ found for Galactic globular clusters of similar absolute magnitude. These are the luminous clusters such as 47 Tuc, Omega Cen, and M54, which have σ ranging from about 12 to 20 km s^{-1}. Adopting a typical value of 16 km s^{-1}, the Tremaine et al. (2002) M_{BH}-σ relation gives a predicted central black hole mass in RZ 2109 of 5000 $M_\odot$.

The present analysis would seem to indicate that not all old, metal-poor stellar systems form black holes consistent with M_{BH}-$M_{stellar}$ and M_{BH}-σ relations found for more massive galaxies. It also indicates that stellar dynamics did not lead to coalesence into an intermediate-mass black hole, at least in this one fairly massive globular cluster. More speculatively, the results suggest that the dark matter halos that presumably surround the early galaxies which grow hierarchically to make massive galaxies at the current epoch are important for retaining gas which is subsequently accreted to fuel the BH growth and set the M_{BH}-σ relation. To further test these conclusions, additional work on forming accreting stellar-mass black hole systems in globular clusters with and without an IMBH would be valuable, as would further understanding of winds driven from systems undergoing mass transfer near or above their Eddington limit. Data with higher spectral resolution would allow a more detailed study of the velocity structure in the [O III] λλ4959, 5007 emission lines which would help constrain the geometry of the emitting material. We also note that the extended nature of the [O III] λ5007 emission in RZ 2109 can be directly tested by spatially resolved spectroscopy with *HST*.

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REFERENCES

Begelman, M. C., King, A. R., & Pringle, J. E. 2006, MNRAS, 370, 399
Bock, J. J., et al. 2000, AJ, 120, 2904
Boroson, T. 2005, AJ, 130, 381
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Dimitrijević, M. S., Popović, L. C., Kovavević, J., Daciś, M., & Ilić, D. 2007, MNRAS, 374, 1181
Freitag, M., Gurkan, M. A., & Rasio, F. A. 2006, MNRAS, 368, 141
Groves, B. A., Cecil, G., Ferruit, P., & Dopita, M. A. 2004, ApJ, 611, 786
Häring, N., & Rix, H. 2004, ApJ, 604, L89
Kinkhabwala, A., et al. 2002, ApJ, 575, 732
Komossa, S., Xu, D., Zhou, H., Storchi-Bergmann, T., & Binette, L. 2008, ApJ, 680, 926
Kulkarni, S. R., Hut, P., & McMillan, S. 1993, Nature, 364, 42
Maccarone, T. J., Kundu, A., Zepf, S. E., & Rhode, K. L. 2007, Nature, 445, 183
Mackey, A. D., Wilkinson, M. I., Davies, M. B, & Gilmore, G. F. 2008, MNRAS, 386, 65
Massey, P., & Gronwall, C. 1990, ApJ, 358, 344
Oke, J. B., et al. 1995, PASP, 107, 375
Osterbrock, D. E., & Ferland, G. J. 2006, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (2nd ed.; Sausalito: Univ. Science Books)
Portegies Zwart, S. F., & McMillan, S. L. W. 2002, ApJ, 576, 899
Proga, D. 2007, in ASP Conf. Ser. 373, The Central Engine of Active Galactic Nuclei, ed. L. C. Ho & J.-M. Wang (San Francisco: ASP), 267
Rhode, K. L., & Zepf, S. E. 2001, AJ, 121, 210
Sánchez-Blazquez, P., et al. 2006, MNRAS, 371, 703
Sigurdsson, S., & Hernquist, L. 1993, Nature, 364, 423
Storey, P. J., & Zeippen, C. J. 2000, MNRAS, 312, 813
Tremaine, S., et al. 2002, ApJ, 574, 740
Yungelson, L.R., van den Heuvel, E.P.J., Vink, J.S., Portegies Zwart, S.F., & de Koter, A. 2008, A&A, 477, 223
Zepf, S. E., Maccarone, T. J., Bergond, G., Kundu, A., Rhode, K. L., & Salzer, J. J. 2007, ApJ, 669, L69 (Z07)