[O \text{iii}] \lambda 5007 EMISSION FROM THE BLACK HOLE X-RAY BINARY IN AN NGC 4472 GLOBULAR CLUSTER\textsuperscript{1,2}

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\section*{ABSTRACT}

We present the discovery of [O \text{iii}] \lambda 5007 emission associated with the black hole X-ray binary recently identified in a globular cluster in the Virgo elliptical galaxy NGC 4472. This object is the first confirmed black hole X-ray binary in a globular cluster. The identification of [O \text{iii}] \lambda 5007 emission from the black hole hosting globular cluster is based on two independent fiber spectra obtained at the VLT with FLAMES, which cover a wavelength range of 5000–5800 Å at a spectral resolution of about 6000. In each of these spectra we find an emission line at 5031.2 Å with an uncertainty of several tenths of an angstrom. These are consistent with [O \text{iii}] \lambda 5007 emission at the 1475 \pm 7 \text{ km s}^{-1} \text{ radial velocity of the globular cluster previously determined from an analysis of its absorption lines. This agreement within the small uncertainties argues strongly in favor of the interpretation of the line as [O \text{iii}] \lambda 5007 emission from the black hole hosting globular cluster. We also find that the emission line most likely has a velocity width of several hundred \text{ km s}^{-1}. Such a velocity width rules out a planetary nebula explanation for the [O \text{iii}] \lambda 5007 emission and implicates the black hole as the source of the power driving the nebular emission.}

\textit{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, hereafter MKZR07) presented the discovery of a black hole X-ray binary in a globular cluster in the Virgo elliptical NGC 4472. This is the first unambiguous black hole X-ray binary in any globular cluster. This result is based on a 100 ks \textit{XMM-Newton} observation of the Virgo elliptical NGC 4472 and its globular clusters. Specifically, MKZR07 identified an X-ray source in a spectroscopically confirmed globular cluster of the Virgo elliptical galaxy NGC 4472 with an X-ray luminosity of $4 \times 10^{38}$ \text{ ergs s}^{-1} \text{ for which the observed count rate varied by a factor of 7 over a few hours. The high X-ray luminosity, about 10 times } L_{\text{bol}} \text{ for a neutron star, rules out any single object other than a black hole in the old stellar population of the globular cluster (MKZR07). However, a high X-ray luminosity alone does not guarantee a black hole source in extragalactic globular clusters, as multiple neutron stars are a possibility in these systems that are unresolved in X-ray data. Variability has long been recognized as a key for distinguishing a black hole X-ray binary from multiple neutron stars in extragalactic globular clusters (e.g., Kalogera et al. 2004). Therefore, the clear variability observed during the \textit{XMM-Newton} observation unambiguously indicates that the high X-ray luminosity in this source originates from a black hole (MKZR07).}

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then good for determining the radial velocity of globular clusters. The fairly high spectral resolution also results in small velocity uncertainties (see Bergond et al. 2006; S. E. Zepf et al. 2007, in preparation). For studying possible emission lines from the black hole X-ray binary, the narrow wavelength range is imperfect. However, it does provide a first look at the spectrum of the unique source, and the spectral resolution corresponding to a velocity width of \( \sim 50 \, \text{km} \, \text{s}^{-1} \) is useful for assessing whether any of the lines are broader than this value.

The bright X-ray source XMUM 122939.7+075333 identified in the XMM-Newton and Chandra images is located at the position of the globular cluster candidate RZ 2109 in the RZ01 cluster sample. The astrometric matching of these catalogs was described in MKZR07, with the agreement good to 0.4", a level similar to the positional uncertainties in the catalogs themselves. As discussed in MKZR07, this excellent agreement gives a negligible probability (\( < 10^{-6} \)) that the X-ray source and globular cluster are not associated with one another. This globular cluster was observed in two of the FLAMES fiber setups described above. One of these was observed for a total of 4.3 hr in 2004 January and the other for 3.2 hr in 2005 April. The reduction of the FLAMES multifiber spectra was carried out in the same way as our previously published analysis of similar data for globular clusters around NGC 3379 (Bergond et al. 2006).

Our standard analysis of the radial velocity of RZ 2109 from the cross-correlation of its absorption lines with stellar templates gives a radial velocity of 1477 \( \pm \) 7 km \( s^{-1} \) for the 2004 January observations and 1460 \( \pm \) 19 km \( s^{-1} \) for the 2005 April observations. We adopt a weighted average of 1475 \( \pm \) 7 km \( s^{-1} \) as the best estimate of the globular cluster radial velocity (in MKZR07 we used the 1477 km \( s^{-1} \) of the observation with the smallest error). The agreement between the two gives high confidence in this radial velocity, and its value unambiguously identifies the object as member of the NGC 4472 globular cluster system, which has a mean radial velocity of 1018 km \( s^{-1} \) and a velocity dispersion of \( \sim 300 \, \text{km} \, \text{s}^{-1} \) (e.g., Zepf et al. 2000).

3. EVIDENCE FOR [O iii] \( \lambda 5007 \) EMISSION

To test for the presence of emission lines in the optical spectrum of XMUM 122939.7+075333, we visually inspected the two independent FLAMES spectra of the object described above. As shown in Figure 1, both spectra show evidence for an emission line at a wavelength corresponding to [O iii] \( \lambda 5007 \) at the radial velocity observed for the host globular cluster. Although the line is only seen at modest signal-to-noise ratio (S/N) in each spectrum, the fact that it is observed in the same place in the two independent spectra, and that it is located precisely at the wavelength of [O iii] \( \lambda 5007 \) redshifted by the radial velocity of the cluster, strongly supports this identification of the line. More specifically, we find the line center to be 5031.5 \( \AA \) in 2004 January spectrum, while in the 2005 April spectrum, we find a line center of 5030.8 \( \AA \) with an uncertainty of several tenths of an angstrom, based on both Gaussian fits and simple mean wavelengths of the continuum-subtracted emission line. We adopt 5031.2 \( \pm \) 0.3 \( \AA \) as the best estimate of the emission-line center. Using a zero redshift wavelength of 5006.8 \( \AA \) for the [O iii] line, we then find a radial velocity of the line of \( \sim 1462 \, \text{km} \, \text{s}^{-1} \) with an uncertainty of \( \sim 18 \, \text{km} \, \text{s}^{-1} \), in excellent agreement with 1475 km \( s^{-1} \) found for the stellar absorption lines of the host globular cluster.

A second key feature of the line seen in each spectrum is that it appears to be broader than the spectral resolution of the data. Specifically, standard Gaussian fits to the line give a FWHM of 4–6 \( \AA \) in both independent spectra. This is much larger than the 0.9 \( \AA \) (4.5 pixels) FWHM of the effective instrumental resolution. The [O iii] \( \lambda 5007 \) line then is clearly intrinsically broad, with a width of \( \sim 200–350 \, \text{km} \, \text{s}^{-1} \). This measured width does not rule out either a weaker, broader component, or detailed structure within the line. However, it does clearly indicate that the overall [O iii] \( \lambda 5007 \) emission is spread over at least a few hundred km \( s^{-1} \).

This observed velocity width strongly implicates the black hole as the source of the energy driving the [O iii] \( \lambda 5007 \) emission. Without a constraint on the line width, the possibility would remain that a planetary nebula in the globular cluster is the source of the [O iii] emission. While these are rare, there are two known cases among the hundreds of extragalactic globular clusters with published spectroscopy (see Bergond et al. 2006 and Pierce et al. 2006 for a NGC 3379 globular cluster, and Minniti & Rejkuba 2002 for a NGC 5128 globular cluster). However, planetary nebulae have velocity widths of tens of km \( s^{-1} \) (Acker et al. 1992 and references therein), and therefore the observed velocity width of several hundred km \( s^{-1} \) eliminates the possibility that the optical emission is from a PN.

The luminosity of the emission line can also be estimated from the spectra. Although flux standards were not observed as part of this program, the target globular cluster has a known magnitude of \( V = 21.0 \) (RZ01). As a result, we can fix the
flux in the continuum to be that for a globular cluster with \( V = 50 \) and use that flux calibration to estimate the observed flux in the [O iii] \( \lambda 5007 \) line. We can also check that the detailed flux distribution across the V band agrees with that expected from models of stellar populations (e.g., Bruzual & Charlot 2003) like that of the globular cluster and its known colors. It is worth noting that the uncertainty in the determination of the total counts in the emission line is substantial, as described below, and thus the uncertainty in this flux calibration contributes negligibly to the error budget of the line luminosity determination.

It is in this way that the flux calibration was estimated for the two spectra shown in Figure 1. An independent check on this calibration can be made by comparing the observed S/N to that expected given the cluster’s known magnitude and the observing conditions, based on the well-characterized throughput of the FLAMES instrument. We find good agreement between these, providing further evidence that the flux estimate is reasonable, and that the uncertainty in the line luminosity is dominated by the measurement of the line itself.

The [O iii] line luminosity can then be determined by measuring the total line flux in the calibrated spectrum, and adopting a distance to NGC 4472 of 16 Mpc (Macri et al. 1999). The most uncertain part of this procedure is determining the total flux in the line and in particular setting the level of the continuum and the range of wavelengths over which to determine the line flux. Our best estimate from both of our spectra in Figure 1 is that \( L([\text{O iii}] \lambda 5007) \) is about \( 4 \times 10^{35} \) ergs s\(^{-1}\). However, if the line is broader than we are able to clearly discern in our data, we estimate this value could be roughly twice as large, and we also find it might be possible to fit the line with a flux that is smaller by 50%. Therefore, we attribute a factor of 2 uncertainty to our \( L([\text{O iii}] \lambda 5007) \approx 4 \times 10^{35} \) ergs s\(^{-1}\) estimate.

4. DISCUSSION

We have shown that optical spectroscopy reveals [O iii] \( \lambda 5007 \) emission associated with the black hole X-ray binary system in a globular cluster around the elliptical galaxy NGC 4472. This [O iii] \( \lambda 5007 \) emission clearly establishes an interaction between the X-ray binary and material around the black hole system. As such, it also provides a potentially valuable test bed for understanding the relation between the binary evolution and accretion history of black holes and their interaction with the surrounding interstellar medium. Our spectra have also been able to establish the general velocity width of the [O iii] \( \lambda 5007 \) line. The several hundred km \( s^{-1} \) width of the line demonstrates that the emission is associated with the black hole X-ray binary since no other cluster source could produce it and also shows that the material may be driven out of the globular, as the velocity width is much larger than the escape velocity of globular clusters.

[O iii] \( \lambda 5007 \) can be produced, in principle, by either collisional or photoionization. We consider each of these possibilities and their implications for the mass of the black hole. In the collisional case, a strong wind is generated by the black hole X-ray binary, which then drives a shock front into the interstellar medium of the globular cluster. We can write standard solutions for the radius \( R \) of this shock front at time \( t \) as

\[
R(t) = 28(M/10^{-6} M_\odot \text{ yr}^{-1})(v_o/20,000 \text{ km s}^{-1})^2 \times (0.1 \text{ cm}^{-3}/n_o)^{1/3} (t/10^3 \text{ yr})^{1/5} \text{ pc}
\]

(e.g., Castor et al. 1975), and the current velocity as \( V(t) = 3/5 R(t)/t \), where \( M \) is the mass-loss rate in the wind, \( v_o \) is the initial velocity, and \( n_o \) is the density of the interstellar medium (ISM). We now consider what likely values for \( n_o, M, v_o \), and \( t \) are and how these might be constrained by current and future observations.

The density of the ISM of globular clusters, \( n_o \), is only well known in a few cases. The best constraint is probably for 47 Tuc, for which the gradient in pulsar dispersion measurements with radial position in the cluster gives a free-electron density of \( 0.067 \pm 0.015 \text{ cm}^{-3} \) (Freire et al. 2003). Similar studies of pulsar dispersion measurements give a similar or slightly higher density in M15 (Freire et al. 2001), and a recent study may have detected somewhat more neutral hydrogen in M15 (van Loon et al. 2006). Most other studies of globular clusters have only been able to place upper limits that are typically well above the adopted value. That there would be some ISM in a globular cluster seems natural, as mass loss from the cluster stars provides a continual source of interstellar material. Even if many processes cause clusters to also lose ISM, the velocities with which this mass is driven out would have to be extraordinarily high, or else the steady state density of the ISM will be generally similar to the fiducial value adopted here (Pfahl & Rappaport 2001).

The radius and current velocity of the shocked region also depend on the kinetic luminosity in the wind, \( M v_o^2 \). In the context of super-Eddington accretion onto a stellar mass black hole, this should be close to the Eddington luminosity of the source and should be independent of the actual accretion rate, providing that it is well above the accretion rate required to yield the Eddington luminosity for an accretion efficiency of 0.1$c^2$ (Belgenjam et al. 2006). The observed X-ray luminosity of \( L_x = 4 \times 10^{39} \) ergs s\(^{-1}\) and an inner disk radius of \( \sim 4000 \) km inferred from the X-ray data (MKZRO7) can be well fit by this model with a \( 10 M_\odot \) black hole accreting at \( \sim 40 \) times the rate required to give the Eddington luminosity.

In this case, the predicted initial wind velocity \( v_i \) is 20,000 km s\(^{-1}\) and \( M \approx 8 \times 10^{-6} M_\odot \). These then give a timescale of \( \sim 2 \times 10^5 \) yr for the bubble to expand to the point where the one-dimensional velocity of the outflow is about 150 km s\(^{-1}\). The corresponding size of the bubble is about 40 pc, which is within the tidal radius expected for a fairly massive outer globular cluster like RZ 2109.

Taken at face value, a model in which \( M \) is constant over the above timescale loses somewhat more mass than the \( 1 M_\odot \) upper limit for a donor star in the globular cluster. However, the detailed application of this model involves many uncertainties, including the level of isotropy of the accretion flow, uncertainties in the radii inferred from X-ray spectroscopy, and inhomogeneity in the ISM along with the effect of input of additional material from ongoing stellar mass loss in the globular cluster. It would then seem a wind-driven system with a constant \( M \) remains feasible.

Alternatively, if the system experiences periods of quiescence, the total mass lost and kinetic power are less than that calculated, assuming these are constant at the above values.

This is because the timescale is the size since the object first became an energetic binary, while \( M \) and thus the kinetic luminosity are the time-averaged values since this time and are thus reduced directly by the duty cycle. In either case, the calculation suggests that a scenario in which a super-Eddington stellar mass black hole driving a strong wind through the ISM of the globular cluster may be able to produce the observed [O iii] \( \lambda 5007 \) emission line. The X-ray data also allow the
possibility that the accretor is an intermediate-mass black hole (IMBH) emitting at sub-Eddington luminosities (MKZKR07). However, a strong wind is not expected in the IMBH sub-Eddington case (Proga 2007 and references therein), so if the [O iii] λ5007 emission is from shocks, then it would seem the black hole has a stellar mass.

We now consider the possibility that the [O iii] λ5007 emission line is photoionized. Because the velocity width of the line is significantly greater than the virial velocity of the globular cluster, if the line is photoionized, it must be produced near the black hole. For a $10^5 M_\odot$ black hole, the velocity width indicates the line must come from $\sim 7 \times 10^4$ cm away from the black hole. This may be possible, although it may prove difficult to have enough mass at the right distance from the black hole to produce the [O iii] λ5007 line luminosity at the observed velocities. For completeness we note that for a stellar mass black hole the observed [O iii] λ5007 seems unlikely to be due to photoionization. The broad lines observed in Galactic black hole X-ray binaries are typically permitted lines such as the Balmer lines and He ii λ4686, as might be expected due to the high densities at the small distances from the central source required to match the velocities. In contrast, as described above, a shock is expected if the accretor is a stellar mass black hole and can produce roughly the observed [O iii] λ5007 emission. A final alternative is that it may be possible for a stellar mass black hole to drive a wind as described earlier but for photoionization of the wind material by the central source to play a significant role in producing [O iii] λ5007.

This analysis shows that understanding the physical process that produces the [O iii] λ5007 emission can place constraints on the mass of the black hole. Determining the mass of the black hole has important implications beyond understanding this individual system. Specifically, it would seem very unlikely to find a stellar mass black hole X-ray binary in a globular cluster with an IMBH. This is because most black holes are believed to be either dynamically ejected (Kulkarni et al. 1993; Sigurdsson & Hernquist 1993) or merge to form an IMBH (Miller & Hamilton 2002). Any surviving stellar mass black hole in a cluster with an IMBH would have to reside in the outer regions of the cluster to avoid either of these fates. However, a location in the outer region of a globular cluster with its low stellar density is not conducive to the stellar dynamical interactions that make close, accreting binaries with black hole primaries in globular clusters. Therefore, it appears that if it can be shown that the black hole must have a stellar mass, then this globular cluster would be very unlikely to host an IMBH. This would then demonstrate that the $M_\bullet - \sigma$ relation for larger mass stellar systems does not hold for all stellar systems at globular cluster masses.

There are several future observations that will help constrain the physical parameters of this interesting system. One of these is expanding the wavelength coverage beyond the narrow region currently available. This will provide line ratio diagnostics such as [S ii]/Hα and [O iii]/Hβ to determine the relative importance of collisional and photoionization processes. As described above, this will have immediate implications for the mass of the accreting black hole, as the currently observed [O iii] λ5007 would seem to require photoionization for an IMBH, while shock ionization works well in the case of a stellar mass black hole. Wider wavelength coverage would also lead to constraints on the density structure in the cluster ISM, and possibly assessing the total power and lifetime of the system.

A key parameter that may be constrained by future observations is the radius at which the [O iii] λ5007 emission originates. We note that at the 16 Mpc distance of NGC 4472, 1" corresponds to 77 pc, so images with much higher spatial resolution than this, such as from HST, may be able to resolve the nebulae and determine its size if it originates in shocks. Correspondingly, a tight upper limit would suggest photoionization, as the spatial scale in this case is orders of magnitude smaller and unresolvable. Moreover, if the line emission originates in shocks, resolving it would allow the size and velocity width to be combined to directly give the timescale, and the total kinetic luminosity would then follow. This would also provide a constraint on whether the accretion has been constant or intermittent, since it is the time-averaged kinetic luminosity that matters for the shock radius while the timescale that matters is the total lifetime of the system.

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