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Deposited 09/12/2018

Citation of published version:

Irwin, J., Brink, T., Bregman, J., Roberts, T. (2010): Evidence for a Stellar Disruption by an Intermediate-Mass Black Hole in an Extragalactic Globular Cluster. *The Astrophysical Journal Letters*, 712(1). <http://dx.doi.org/10.1088/2041-8205/712/1/L1>

## EVIDENCE FOR A STELLAR DISRUPTION BY AN INTERMEDIATE-MASS BLACK HOLE IN AN EXTRAGALACTIC GLOBULAR CLUSTER\*

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Received 2009 August 7; accepted 2010 January 19; published 2010 February 24

### ABSTRACT

We report [O III]  $\lambda 5007$  and [N II]  $\lambda 6583$  emission from a globular cluster harboring the ultraluminous X-ray source CXOJ033831.8–352604 in the Fornax elliptical galaxy NGC 1399. No accompanying Balmer emission lines are present in the spectrum. One possibility is that the forbidden lines emanate from X-ray-illuminated debris of a star that has been tidally disrupted by an intermediate-mass black hole, with this debris also feeding the black hole leading to the observed X-ray emission. The line strengths indicate that the minimum size of the emitting region is  $\sim 10^{15}$  cm, and if the 70 km s<sup>-1</sup> half-widths of the emission lines represent rotation around the black hole, a minimum black hole mass of 1000  $M_{\odot}$  is implied. The non-detection of H $\alpha$  and H $\beta$  emission lines suggests a white dwarf star was disrupted, although the presence of strong nitrogen emission is somewhat of a mystery.

*Key words:* galaxies: individual (NGC 1399) – galaxies: star clusters: general – globular clusters: general – X-rays: binaries – X-rays: galaxies: clusters

### 1. INTRODUCTION

Despite decades of effort, finding clear-cut evidence for the existence of intermediate-mass black holes (IMBHs; 100–10<sup>4</sup>  $M_{\odot}$ ) within globular clusters has proved quite elusive. Initial claims of kinematical evidence for a >1000  $M_{\odot}$  black hole in the Milky Way globular M15 as far back as the 1970s (Newell et al. 1976) have been vigorously questioned over the years (Illingworth & King 1977; McNamara et al. 2003). Further claims of IMBHs in the Milky Way globular clusters NGC 6388 (Lanzoni et al. 2007) and Omega Cen (Noyola et al. 2008) as well as G1 in M31 (Gebhardt et al. 2002) also have not been met with universal acceptance (Baumgardt et al. 2003; Nucita et al. 2008; van der Marel & Anderson 2010).

If IMBHs exist within globular clusters they should occasionally disrupt passing stars, either tidally shredding them or inducing a supernova explosion in the event a white dwarf (WD) strays too close (Frank & Rees 1976; Baumgardt et al. 2004; Rosswog et al. 2008; Ramirez-Ruiz & Rosswog 2009). Such an event would leave unique transitory optical, ultraviolet, and X-ray signatures lasting years to perhaps centuries. In this Letter, we present the discovery of [N II]  $\lambda 6583$  and [O III]  $\lambda 5007$  emission from the globular cluster that harbors the ultraluminous X-ray source (ULX) CXOJ033831.8–352604 in the Fornax elliptical galaxy NGC 1399. We explore the idea that the X-ray emission and optical emission lines result from the aftermath of the tidal disruption of a WD by an IMBH in this globular cluster.

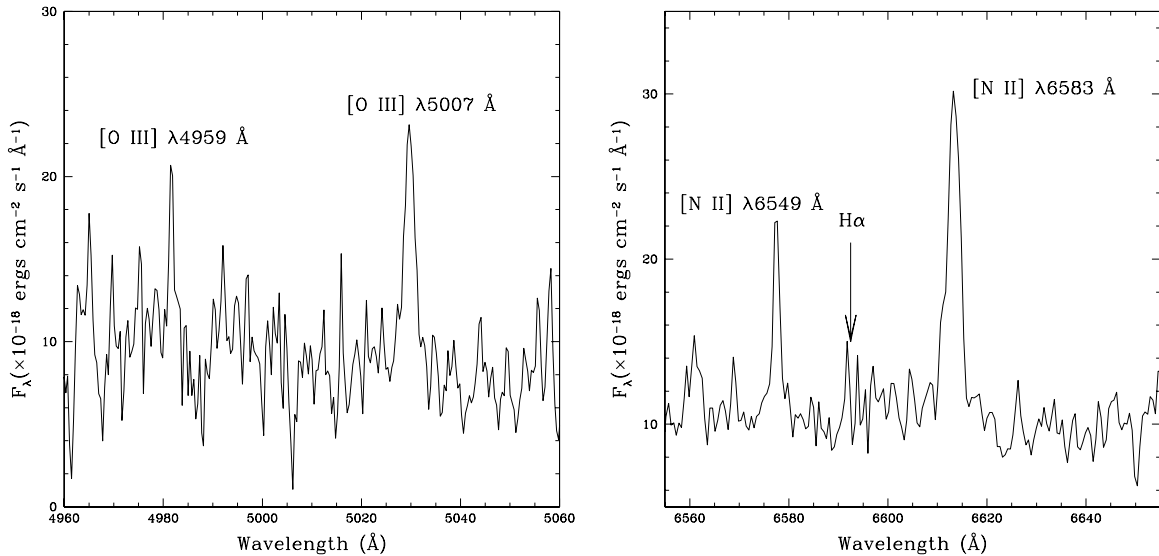
### 2. OPTICAL AND X-RAY OBSERVATIONS

CXOJ033831.8–352604 was first identified as a globular cluster X-ray source by Angelini et al. (2001), with the host globular cluster being quite luminous and red ( $B - I = 2.25$ ,  $M_I = -10.5$ ; Kundu et al. 2007 assuming  $d = 20$  Mpc). We observed the globular cluster for 1 hr on 2005 October 10 with the Low Dispersion Survey Spectrograph (LDSS-3) mounted

on the Magellan II Clay 6.5 m Telescope (Las Campanas Observatory, Chile), again on 2006 November 26–27 for 4 hr with the Inamori Magellan Areal Camera and Spectrograph (IMACS) on the Magellan I Baade Telescope, and finally on 2008 October 27 for 7.5 hr with the Magellan Echellette Spectrograph (MagE) on the Magellan II Clay Telescope. Superimposed on the continuum emission from the globular cluster is an emission line at 6613 Å detected in all three observations, and a second emission line at 5029 Å detected in the final two observations (the LDSS-3 observation was not sensitive below 6000 Å). Both emission lines are doublets and correspond to [N II]  $\lambda 6583$  and [O III]  $\lambda 5007$  at a recessional velocity of 1360 km s<sup>-1</sup>. This is consistent with the velocity measured for the Ca II triplet (1360–1372 km s<sup>-1</sup>) and Na I D doublet (1354–1362 km s<sup>-1</sup>) absorption lines in the globular cluster spectrum and with the recessional velocity of NGC 1399 itself.

The emission lines were resolved in the MagE spectrum (instrumental FWHM = 55 km s<sup>-1</sup>) with an FWHM of 140 km s<sup>-1</sup>. The luminosity of each line was few  $\times 10^{36}$  erg s<sup>-1</sup>. The regions of the flux-calibrated MagE spectrum around the two emission lines are shown in Figure 1. Figure 1 also illustrates the lack of H $\alpha$  in the spectrum. In determining the uncertainties to line emission, we made fits to the emission lines, using a Gaussian line profile, where the fitted quantities were the continuum level, line center, line width, and line amplitude. Fits to the lines had acceptable  $\chi^2$  values and errors were calculated in the usual way, as  $\chi^2$  deviations that correspond to 1 $\sigma$ , etc. Upper limits to undetected line emission were obtained by similar line-fitting techniques, except that the line center was fixed (so we assumed that all lines have the same velocity) and the line width was fixed at the value from other lines. A line amplitude and its error were determined in each case. The line amplitude had a signal-to-noise ratio (S/N) <2 in those cases (often, less than 1 $\sigma$  and often with the wrong sign). Based on the error, 3 $\sigma$  upper limits were formed. Balmer absorption from the globular cluster could be affecting the detection of any Balmer emission lines. Using the spectra of other globular clusters of similar luminosity, metallicity, and S/N obtained with the same IMACS setup,

\* This Letter includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.



**Figure 1.** 7.5 hr flux-calibrated MagE spectrum of the globular cluster harboring CXOJ033831.8–352604 illustrating the [O III] (left) and [N II] (right) emission lines. Note the lack of  $H\alpha$ .

we did not detect any Balmer absorption lines, and found that the upper limits on Balmer features were no different than in CXOJ033831.8–352604. This indicates that statistical uncertainties in the continuum level dominate any Balmer absorption. Therefore, we use the IMAC-only determination of the upper limit on Balmer emission in our line ratio calculations. By summing the statistics of all three observations for [N II] and [O III], we can place a  $3\sigma$  lower limit on [N II]/ $H\alpha$  of 7. We can also place a  $3\sigma$  lower limit on [O III]/ $H\beta$  of 5. Utilizing the IRAF line diagnostic routine TEMDEN, we can use the lack of a [N II]  $\lambda 5755$  detection to place a  $3\sigma$  upper limit on the temperature of the emitting region of 13,000 K if a single-temperature model with a density equal to the critical density of [N II] is assumed.

To determine whether we should have detected the double-horn profile indicative of rotation, we convolved a double-horn velocity profile with a Gaussian of  $55 \text{ km s}^{-1}$  (the spectral resolution of MagE). For the rotational line shape, we took a rotating ring, which produces the sharpest double-horned profile. The rotational velocity was chosen so that the convolved profile has the same width as the observed profile. At our spectral resolution, the double-horned profile appears nearly as a single-peaked profile with only a small local minimum at line center. At the S/N of our data, this model is not distinguishable from a Gaussian profile.

CXOJ033831.8–352604 has been observed with *Chandra* on eight occasions over the past decade. The data were processed in a uniform manner following the *Chandra* data reduction threads using CIAOV3.4. An extraction region representing the 90% enclosed flux aperture for a point source at the position of CXOJ033831.8–352604 on the detector was assumed. Spectra were extracted and responses were generated using the CIAO tool SPEXTRACT with local background chosen from an annulus surrounding the source. The spectra were grouped to contain 25 counts per channel. Channels with energies  $<0.5 \text{ keV}$  and  $>8.0 \text{ keV}$  were excluded. The spectra were fit within XSPEC with a simple power-law model absorbed by the Galactic hydrogen column density toward NGC 1399 ( $N_{\text{H}} = 1.34 \times 10^{20} \text{ cm}^{-2}$ ; Dickey & Lockman 1990). A disk blackbody model absorbed by the Galactic hydrogen column density was also employed.

Only three of the *Chandra* observations yielded a useful spectrum ( $>100$  counts). Observations 0319 (2000 January 18), 4172 (2003 May 26), and 9530 (2008 June 6) yielded best-fit power-law exponents with 90% uncertainties of  $2.5 \pm 0.2$ ,  $3.0 \pm 0.5$ , and  $2.5 \pm 0.4$ , and 0.3–10 keV luminosities of  $2.3$ ,  $1.6$ , and  $1.5 \times 10^{39} \text{ erg s}^{-1}$ , respectively, with  $\chi^2_{\nu}$  values near unity. Using a disk blackbody model instead yielded best-fit temperatures of  $0.38 \pm 0.04$ ,  $0.39 \pm 0.08$ , and  $0.36 \pm 0.07 \text{ keV}$ , respectively, and luminosities about 30% lower than in the power-law fits.

### 3. UNLIKELINESS OF PLANETARY NEBULA OR SUPERNOVA REMNANT EXPLANATIONS

Optical emission lines emanating from extragalactic globular clusters are unusual, with an estimated occurrence rate of a few percent at most based on literature searches. Those found are usually attributed to planetary nebulae (Larsen 2008) or supernova remnants (Peng et al. 2004). Chomiuk et al. (2008) found two [O III] emission-line globular clusters in the S0 galaxy NGC 7457 which are believed to be a planetary nebula and a supernova remnant. However, none of these globular clusters are associated with luminous X-ray sources. Globular clusters harboring X-ray sources with  $L_{\text{X}} > 2 \times 10^{39} \text{ erg s}^{-1}$  are even rarer; CXOJ033831.8–352604 is the third brightest X-ray source in a globular cluster of the tens of thousands of globular clusters around all galaxies imaged by *Chandra* within 20 Mpc. The odds of both events occurring independently in an average globular cluster are  $\lesssim 10^{-5}$ , so the odds for a 10 times more massive globular cluster like the one harboring CXOJ033831.8–352604 is  $\lesssim 10^{-3}$ . We will therefore focus on explanations that account for both the high X-ray luminosity and optical emission lines in terms of a single object.

While planetary nebulae are sources of strong [O III]/[N II] emission, their X-ray luminosities are orders of magnitude lower than CXOJ033831.8–352604. Furthermore, very few planetary nebulae in the Milky Way have [N II]/ $H\alpha$  ratios as high as 7 (Riesgo & López 2006), nor do they have expansion velocities of  $70 \text{ km s}^{-1}$ . Supernova remnants can be strong [O II] emitters and on rare occasion have  $L_{\text{X}} > 10^{38} \text{ erg s}^{-1}$  (Patnaude & Fesen 2003; Bauer et al. 2008). However, in order for the expansion

of the remnant to have slowed down from an initial velocity of  $\sim 10^4$  km s $^{-1}$  to the measured velocity of  $\sim 70$  km s $^{-1}$  (assuming the width of the line is interpreted as expansion rather than rotation), the remnant would have needed to sweep up a substantial amount of interstellar medium (ISM) within the globular cluster. Assuming there is even enough ISM (primarily hydrogen) in the globular cluster to slow down the expansion, we would expect to detect significant H $\alpha$  emission as is seen in most supernova remnants. Furthermore, supernova remnants do not show such large [N II]/H $\alpha$  ratios (Payne et al. 2007, 2008).

#### 4. STELLAR DISRUPTION BY AN IMBH?

The luminous, persistent nature of the X-ray source argues that an accreting black hole is the source of the X-ray emission. For more than eight years, the source has shone at 10 times the Eddington limit of a neutron star. The X-ray luminosity of CXOJ033831.8–352604 is consistent with either a stellar-mass black hole accreting near its Eddington limit, or an IMBH accreting at 0.1%–1% of its Eddington limit. Here, we explore the idea that the observed X-ray and optical properties of CXOJ033831.8–352604 are best described as the aftermath of a tidal disruption event of a star passing by an IMBH within the globular cluster.

The idea that IMBHs within globular clusters will tidally disrupt passing stars has been increasingly explored recently.  $N$ -body simulations show a  $1000 M_{\odot}$  IMBH at the center of a globular cluster should tidally disrupt a passing star every  $10^5$ – $10^9$  years depending on the central density of the globular cluster (Baumgardt et al. 2004). A host of studies (involving both  $10^6 M_{\odot}$  supermassive black holes in galactic nuclei and IMBHs in globular clusters) predicts the debris from the disrupted star forms a precessing, self-interacting stream, which ultimately forms an accretion disk, an optically thick envelope, and a quasi-spherical  $\sim 10^4$  K diffuse photosphere extending to  $\sim 10^{15}$  cm or larger. Accretion of the debris material by the black hole leads to an intense, short-lived (few months) UV/soft X-ray flare peaking near the Eddington limit (Rees 1988; Loeb & Ulmer 1997; Ulmer et al. 1998) followed by a less intense accretion phase lasting much longer (Cannizzo et al. 1990; Ulmer et al. 1998) where the X-ray luminosity is predicted to decline as  $t^{-5/3}$ . During this less intense accretion phase, it is expected that the optically thick envelope and diffuse photosphere from the stellar debris reprocess the X-ray emission from the accretion disk to the optical/UV part of the spectrum (Loeb & Ulmer 1997; Bogdanović et al. 2004; Sesana et al. 2008). Work by Ramirez-Ruiz & Rosswog (2009) indicates that an IMBH-induced tidal disruption event could continue to emit at  $L_X > 10^{39}$  erg s $^{-1}$  for more than a century after the disruption event and suggest that line emission from globular clusters might earmark the presence of recent tidal disruption events. A variation on the tidal disruption theme is if the passing star is a WD that experiences such strong tidal forces by an IMBH that its core is compressed to the point thermonuclear detonation is triggered (Rosswog et al. 2008). An underluminous, Type Ia supernova-like event would then occur with debris being ejected from the globular cluster at high velocities.

The modest widths of the [O III] and [N II] lines of CXOJ033831.8–352604 argue against a thermonuclear *detonation* tidal event, but might represent rotation of material around the black hole following a tidal *disruption* event. In this scenario, the X-ray emission results from debris material falling onto the black hole, while the [O III] and [N II] emission lines

emanate from the reprocessing of escaping X-ray photons by material in the diffuse photosphere. The upper limit on the temperature of the line-emitting region of 13,000 K from [N II] line diagnostics is consistent with the predicted temperature of the diffuse photosphere. The 35% decline in X-ray luminosity from 2000 to 2008 is not necessarily incompatible with the predicted  $t^{-5/3}$  decline if the actual tidal event took place a century ago. The soft X-ray spectrum is also similar to suspected tidal disruption events from supermassive black holes, such as in NGC 3599 and SDSS J132341.97+482701.3, whose X-ray spectra remained soft ( $\Gamma \sim 3$ ) several years after discovery, when the X-ray emission had faded 3 orders of magnitudes from their Eddington flare peaks (Esquej et al. 2008).

With the assumption that the [O III] and [N II] lines represent rotation of debris material around an IMBH, we can use the strength of the forbidden [O III] and [N II] lines to place a lower limit on the size of the emitting region, and therefore a lower limit on the mass of the IMBH. The luminosity of the line can be expressed as  $L = \epsilon_v n_e n_{\text{ion}} V$ , where  $\epsilon_v$  is the emissivity of the line per unit electron ( $n_e$ ) and unit ion ( $n_{\text{ion}}$ ) densities, and the emitting volume,  $V$ , is  $4/3\pi R^3$ . We can place an upper limit on  $n_e$  of  $8 \times 10^4$  cm $^{-3}$  since this is the critical density of [N II], and we would not observe [N II] if  $n_e$  were substantially higher. Assuming  $n_{\text{ion}} \sim n_e$ , we can then place a lower limit on  $R$ , the physical size of the emitting region. The [N II] line has a luminosity of  $3 \times 10^{36}$  erg s $^{-1}$ , leading to a lower limit on  $R$  of  $\sim 3 \times 10^{15}$  cm. Coupled with a rotation velocity of 70 km s $^{-1}$ , this leads to a lower limit of the black hole mass of  $\sim 1000 M_{\odot}$ .

The argument that we present does not critically depend on the gas being in rotational equilibrium. It depends on the line width being indicative of the depth of the potential well. For non-explosive events (not supernova or nova events), the outflow, inflow, or turbulent velocity is expected to have an energy similar to the potential well at that point,  $v^2 \approx GM/R$ . This is the situation for the broad-line region in active galactic nuclei (AGNs), for example, which is used to determine masses of supermassive black holes. In the AGN case, the distance to the emitting-line region comes from reverberation line mapping. In our case, the lower limit on the distance is determined from the need for the emitting region to have a density below the critical density of [N II].

Another argument in favor of an IMBH rather than a stellar-mass black hole for the disrupting object is the expected timescale of decline of the X-ray emission following the disruption event. Following the Eddington flare, the X-ray luminosity should decay as  $t^{-5/3}$  (and possibly as  $t^{-1.2}$  at later times; Ramirez-Ruiz & Rosswog 2009). A  $< 100 M_{\odot}$  black hole would have a peak X-ray luminosity of a  $< \text{few} \times 10^{40}$  erg s $^{-1}$ . A  $100 M_{\odot}$  black hole would have to have been accreting at 10% its Eddington limit in 2000, indicating a disruption event no more than a year earlier. By 2008, the X-ray emission should have declined 2 orders of magnitude, rather than the measured 35%. However, a several thousand solar mass black hole would flare to  $\sim 5 \times 10^{41}$  erg s $^{-1}$ , and would take some time (decades) to decay down to the observed  $1.5$ – $2.3 \times 10^{39}$  erg s $^{-1}$ , indicating the disruption took place some time ago.

The lack of Balmer emission in the spectrum suggests that the disrupted star was a WD. However, the presence of such a strong nitrogen emission line from WD material is somewhat puzzling. The AM Cvn star GP Com (a double WD binary) shows nitrogen and oxygen in the optical (Marsh et al. 1991), and nitrogen in X-ray (Strohmayer 2004), although the unusual evolutionary path needed to create a system like GP Com seems

untenable in a binary with an IMBH primary. There are a few ultracompact binaries believed to have helium WD star donors for which significant nitrogen is detected from the accretion disk (Nelemans et al. 2006), but in these instances helium is also clearly detected, unlike in CXOJ033831.8–352604. Further modeling of the optical spectrum of CXOJ033831.8–352604 will be required to determine if such large amounts of helium could be present but undetected given the physical conditions of the gas that is emitting the [N II]/[O III] lines. If the disrupted star was a helium WD, then our assumption that  $n_{\text{ion}} \sim n_e$  is inaccurate, in the sense that a lower  $n_{\text{ion}}$  is implied for a given  $n_e$ . This will increase the lower limit of the mass estimate of the black hole.

There is another source that shares similarities with CXOJ033831.8–352604. Zepf et al. (2007, 2008) reported [O III]  $\lambda$ 5007 emission from the ULX-harboring globular cluster RZ2109 in the Virgo elliptical galaxy NGC 4472. Both RZ2109 and CXOJ033831.8–352604 exhibit strong [O III] emission, both show a lack of H $\alpha$  and H $\beta$  emission, and the X-ray spectra of both sources are quite soft. However, while CXOJ033831.8–352604 harbors strong [N II] emission with a flux greater than the [O III], the upper limit on the [N II]/[O III] ratio for RZ2109 is only a few percent. Also, the [O III] luminosity of RZ2109 is an order of magnitude larger than in CXOJ033831.8–352604. Furthermore, the measured width of the [O III] line of RZ2109 is  $\sim 1500 \text{ km s}^{-1}$ , whereas the widths of the [N II] and [O III] lines of CXOJ033831.8–352604 are an order of magnitude narrower.

Zepf et al. (2008) point out that the  $\sim 1500 \text{ km s}^{-1}$  width of the [O III] line of RZ2109 is too broad to represent rotation around a black hole unless the black hole is unrealistically massive. Instead, Zepf et al. (2008) argue that the most reasonable explanation for the X-ray/optical properties of RZ2109 is that the X-ray emission from the black hole is photoionizing material blown by a black hole wind. They argue that since AGN winds are only blown by black holes accreting near their Eddington limit, the black hole in RZ2109 must also be accreting near its Eddington limit. As the peak X-ray luminosity of RZ2109 is  $4 \times 10^{39} \text{ erg s}^{-1}$ , a stellar-mass black hole is implied. In this case, the donor star is most likely a WD to explain the lack of hydrogen lines, making the system an ultracompact binary.

The wide [O III] line might suggest a different scenario: an IMBH in RZ2109 has tidally detonated a WD that passed sufficiently close in a supernova-like event, as described in the numerical simulations of Rosswog et al. (2008), and we are seeing the aftermath of this event, as a supernova remnant is being formed. fallback of debris from the detonation event could lead to the X-ray emission. If oxygen had been torn from the WD during a previous passage, or if undetonated oxygen in the outer layers of the WD was swept up by the fast-moving expanding ejecta, such a wide [O III] line might result from the photoionization of this material by the X-ray emission. The lack of an appreciable ISM explains the lack of Balmer lines typically seen in Type Ia supernova. Further work is needed to determine if such a scenario can reproduce the observed X-ray and optical line emission characteristics. Specifically, the physical conditions (density, temperature, velocity) under

which the shape and strength of the [O III] line can be produced without accompanying emission from Fe from the supernova ejecta will need to be investigated. Such modeling will need to take into account the unusual conditions of such a scenario compared to a classical Type Ia supernova, for example, the potential presence of circumstellar oxygen that was stripped from the WD on previous encounters with the IMBH prior to the detonation event. The long-term X-ray light-curve variations of RZ2109 (Shih et al. 2008) will also need to be shown to be consistent with a fallback scenario.

We thank Jon Miller, Tom Richtler, Stephanie Komossa, and Jari Kajava for useful discussions. We also thank an anonymous referee for helpful suggestions. This work was supported by NASA LTSA grant NNG05GE48G and *Chandra* grant GO8–9087X.

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