A STRINGENT LIMIT ON THE ACCRETION LUMINOSITY OF THE POSSIBLE CENTRAL BLACK HOLE IN THE GLOBULAR CLUSTER M15
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ABSTRACT

The globular cluster M15 has recently been found to host a possible central black hole with a mass of \( \sim 2000 \, M_\odot \). A deep, high-resolution \textit{Chandra} image failed to detect the “nucleus” of the cluster in X-rays. The upper limit on the X-ray luminosity (\( L_x \lesssim 5.6 \times 10^{32} \, \text{erg} \, \text{s}^{-1} \)) corresponds to a bolometric Eddington ratio of \( L_{\text{bol}} / L_{\text{Edd}} \lesssim (2-4) \times 10^{-8} \). Combining this limit with an estimate of the electron density of the intracluster ionized plasma derived from pulsar dispersion measures, we show that the radiative efficiency of the accretion flow, if it accretes at the Bondi rate, must be much lower than that of a standard optically thick, geometrically thin disk.

Subject headings: black hole physics — globular clusters: individual (M15) — X-rays: general

1. INTRODUCTION

The discovery of X-ray sources in Galactic globular clusters nearly 30 years ago (Giacconi et al. 1974; Canizares & Neighbours 1975; Clark, Markert, & Li 1975) prompted speculation that central massive (\( \sim 100-1000 \, M_\odot \)) black holes (BHs) may exist in these systems (Bahcall & Ostriker 1975; Silk & Arons 1975). In this respect, M15, one of the densest globular clusters detected in X-rays, historically has been scrutinized most thoroughly (see review by van der Marel 2001). Often regarded as a prototypical core-collapsed globular cluster (Djorgovski & King 1986), M15 has a projected stellar density profile that rises steeply toward the center (Guhathakurta et al. 1996; Sosin & King 1997), seemingly in excellent agreement with models for the distribution of stars around a massive collapsed object (Peeples 1972; Bahcall & Wolf 1976). Unfortunately, core collapse of the cluster, induced by two-body relaxation, can produce density profiles that closely mimic those generated by the influence of a BH (Grabhorn et al. 1992), and thus the photometric evidence for a BH remained ambiguous. Kinematic data can provide a much more definitive probe of the central mass distribution. However, despite numerous efforts (e.g., Peterson, Sitter, & Cudworth 1989; Dubath & Meylan 1994; Gebhardt et al. 1994, 1997; Dull et al. 1997; Drukier et al. 1998), the ground-based spectroscopic studies of M15 have met with only limited success. This is largely due to the tremendous difficulty of measuring radial velocities for individual stars in the crowded cluster core, even under conditions of exceptional seeing. As summarized in the latest study by Gebhardt et al. (2000), the central kinematics of M15 are consistent with the presence of a \( 2500 \, M_\odot \) dark object, but the data can be equally well fitted with a mild, not unreasonable, increase in the mass-to-light ratio toward the center.

A major breakthrough was recently achieved in the search for the elusive central BH in M15. Using a series of longslit spectra taken with the \textit{Hubble Space Telescope}, van der Marel et al. (2002) and Gerssen et al. (2002, 2003) significantly increased the sample of radial velocities measured within the cluster core, thereby permitting a more robust analysis of the central kinematics. The data indicate the presence of a central dark mass, although its nature is still unclear. Models with a BH mass of \( \sim 2000 \, M_\odot \) provide a marginally better fit to the data than those without one, but not at a statistically significant level of confidence (Gerssen et al. 2002, 2003). The dynamical simulations of Baumgardt et al. (2003) show that a central concentration of non-luminous, massive stellar remnants can account for the data equally well. This explanation, however, is uncertain because it depends on the assumption that all the neutron stars are retained in the cluster (Baumgardt et al. 2003; Gerssen et al. 2002, 2003). Thus, a massive BH cannot be ruled out in M15.

In a parallel study, Gebhardt, Rich, & Ho (2002) announced the detection of a \( 2 \times 10^4 \, M_\odot \) BH in G1, a luminous globular cluster in the galaxy M31. This finding lends additional confidence to the BH interpretation for the case of M15.

The possible existence of central massive BHs in star clusters opens up many new avenues of investigation. Particularly interesting is the prospect of probing accretion physics in the “active nucleus” of the cluster, by direct analogy with the study of active galactic nuclei in external galaxies. Nearby stellar clusters potentially offer a completely fresh vantage point for studying nuclear activity. In contrast to extragalactic nuclei, Galactic clusters are well resolved into individual stars, and their structure and dynamics are much better understood.

This paper reports sensitive, high-resolution \textit{Chandra} observations of the central region of M15. The nucleus is not detected in X-rays, down to an exceedingly stringent limit of \( \sim 2.2 \times 10^{-9} \) of the Eddington luminosity of a \( 2000 \, M_\odot \) BH. We combine this measurement with estimates of the central gas density to constrain the radiative efficiency of the accretion flow.

2. OBSERVATIONS AND RESULTS

Our analysis is based on archival data (PI: J. E. Grindlay) acquired with \textit{Chandra} (Weisskopf, O’Dell, & van Speybroeck 1996) using the High Resolution Camera (HRC-I; Murray et al. 1997). HRC-I has a field of view of \( 30' \times 30' \) and a pixel scale of \( 0.13' \), which well samples the point-spread function (PSF) of the telescope (FWHM \( \approx 0.4' \)). There are a total of three observations, performed on 2001 July 13, August 3, and
August 22. The effective exposure times are 9.1, 8.8, and 10.8 ks, respectively. We analyzed the data sets separately, and then combined.

Figure 1 shows the central $7''8 \times 10''$ of the HRC-I image. As recently demonstrated by White & Angelini (2001) using a *Chandra* ACIS image, the X-ray source 4U 2127+119 in fact consists of two sources separated by 2$''$7: AC 211, a low-mass X-ray binary (LMXB) with a previously known bright optical counterpart, and M15 X-2, another LMXB that is coincident with a faint, blue star ($U \approx 19$ mag). The *Chandra* positions of the two bright sources were compared with previous measurements [radio position of AC211 from Kulkarni et al. (1990); X-ray position of M15 X-2 from White and Angelini (2001)] and found to be offset by $\sim 0''2$. We shifted the images by this amount to align the X-ray and radio positions of AC211.

The position of the cluster center (Gerssen et al. 2002), $\alpha = 21^h 29^m 58.35 s, \delta = 12^\circ 10' 0.89''$ (J2000), shows no significant counts in excess of the extended wings of the PSF from AC 211. This is illustrated quantitatively in Figure 2, which gives a one-dimensional projection of the surface brightness along the cluster center and AC211. The profile, derived by summing over a width of 6 pixels ($0''78$), is used to model the shape of the PSF of AC211 and to calculate an upper limit on the nuclear flux. The choice of the width affects the following results only slightly. For both the first and second observations, the profile of AC211 is well fitted with a model consisting of a Gaussian and a Lorentzian, representing the core and the extended wings of the PSF, respectively. We note that this model is not an accurate representation of the PSF for data with very good photon statistics. Indeed, the third observation AC211 is about four times brighter than in the first and second observations, and systematic errors in the PSF model dominate over photon statistics. In order to use our simple PSF model, we concentrate only on the first two observations.

We calculated an upper limit on the count rate from the nucleus by adding a Gaussian, whose width was fixed to the value determined from AC211, to model the emission from the cluster center. Since the core of the PSF is well described by a Gaussian, a single Gaussian provides a reasonable description of the PSF shape for the very faint central source. We employed a maximum likelihood method in the fits because of the small number of counts in the tail of the profile. The errors on the counts were estimated using the approximation of Gehrels (1986).

Since M15 X-2 is roughly equidistant from the cluster center and the opposite side of AC211 (right-hand side in Fig. 2), the tail of its PSF should contribute roughly equally to both positions, provided that the PSF does not vary strongly with azimuth. We examined the azimuthal angle dependence of the PSF by using an observation of 3C 273. We find that any variation is at most $\pm 10\%$ (including statistical error) at $2''$ from the PSF peak, approximately the distance between AC211 and the cluster center.

We repeated these measurements for the first, second, and the combined profile of the two observations. The Gaussian component for the cluster center was not required statistically in any of the fits. The 90% confidence upper limit (one parameter of interest) on the count rates are 0.0059, 0.0043, and 0.0033 counts s$^{-1}$, respectively. To convert the limit on the count rate to an X-ray flux, we assumed (1) that the spectrum between 0.2 and 10 keV can be described by a power law with a photon index of 2.3, a spectral model that fits well the quiescent nucleus of the Galaxy (Baganoff et al. 2001) and M32 (Ho, Terashima, & Ulvestad 2003), (2) that the line-of-sight absorbing column $N_H = 5.8 \times 10^{20}$ cm$^{-2}$, calculated from $E(B-V) = 0.10$ mag (Harris 1996) and the relation $N_H = 5.8 \times 10^{21} E(B-V)$ cm$^{-2}$ (Savage & Mathis 1979), and (3) the latest effective area for the combination of the high-resolution mirror assembly and the HRC (version 2.1). These assumptions give $F_x < 4.4 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ for the combined observations, or $L_x < 5.6 \times 10^{32}$ erg s$^{-1}$ assuming a distance of 10.4 kpc (Harris 1996).

3. IMPLICATIONS

The nucleus of M15, if presumed to host a $\sim 2000 M_{\odot}$ BH, is extremely inactive. The upper limit on the X-ray luminosity derived from the *Chandra* observations corresponds to an Eddington ratio of $L_x / L_{\text{Edd}} \lesssim 2.2 \times 10^{-8}$, where $L_{\text{Edd}} = 1.26 \times 10^{38} (M / M_{\odot})$ erg s$^{-1}$. Judging from the broad-band spectral energy distributions of galactic nuclei over a wide range of activity levels (Elvis et al. 1994; Ho 1999), the bolometric correction for the X-ray band is $\sim 7 - 20$. Hence, $L_{\text{bol}} / L_{\text{Edd}} \lesssim (2 - 4) \times 10^{-8}$.

Why is the nuclear BH of M15 so quiescent? One possibility is that the cluster is completely devoid of gas. Although post-main sequence stars continuously inject mass into the intracluster medium through mass loss, a variety of mechanisms can effectively remove it (e.g., Frank & Gisler 1976; Spertzel 1991; Smith 1999). Indeed, nearly all efforts to detect gas, be it...
neutral or ionized, in globular clusters have resulted in null detections (see Knapp et al. 1996, and references therein). While low, however, the gas content is not zero, and it would be of interest to estimate how much accretion luminosity one might expect to see. Dispersion measures derived from radio observations of pulsars provide the most sensitive probe of the line-of-sight integrated column density of free electrons in globular clusters. From an analysis of the population of millisecond pulsars in 47 Tucanae and M15, Freire et al. (2001) find an electron density of \( n_e \approx 0.1 \) and 0.2 cm\(^{-3}\), respectively. We expect the plasma, which has been photoionized by the ultraviolet radiation field from post-asymptotic giant branch stars, to have a temperature \( T_e \approx 10^4 \) K. To first order, this temperature is consistent with the value derived assuming that the gas is in virial equilibrium with the stars. For a central stellar velocity dispersion of \( \sigma = 14 \) km s\(^{-1}\) (Gerssen et al. 2002), \( T = \mu m_p\sigma^2/k \approx 3 \times 10^4 \) K, where \( \mu \) is the mean atomic weight, \( m_p \) is the proton mass, and \( k \) is Boltzmann’s constant.

Let us assume that low-angular momentum gas in the vicinity of the BH accretes spherically, as described by Bondi (1952). The gravitational potential of the BH dominates the dynamics of the gas within the accretion radius, \( R_A \approx GM/c_s^2 \), where \( c_s \approx 0.1T_8^{1/2} \) km s\(^{-1}\) is the sound speed of the gas. For \( T_e = 10^4 \) K and \( M = 2000 M_\odot \), \( c_s \approx 10 \) km s\(^{-1}\) and \( R_A \approx 0.1 \) pc (\( \sim 2\alpha \) at the distance of M15). From the continuity equation, the Bondi accretion rate \( \dot{M}_B \approx 4\pi R_A^2 \rho_0 c_s \), where \( \rho_0 \) is the gas density at \( R_A \). Expressed in terms of parameters appropriate for M15,

\[
\dot{M}_B \approx 4.8 \times 10^{-9} \left( \frac{M}{2000 M_\odot} \right)^2 \left( \frac{n}{0.2 \text{ cm}^{-3}} \right) \left( \frac{10 \text{ km s}^{-1}}{c_s} \right)^3 M_\odot \text{ yr}^{-1}
\]

If this emission is produced by an optically thick, geometrically thin disk (Shakura & Sunyaev 1973), the accretion luminosity is \( L_{\text{acc}} = \eta \dot{M}c^2 \approx 3 \times 10^{37} (\eta/0.1) \) erg s\(^{-1}\), where we have assumed a canonical radiative efficiency of \( \eta = 0.1 \) and \( M = M_B \). This high value of the accretion luminosity clearly contradicts the observational upper limit of \( L_{\text{bol}} \approx (4 - 11) \times 10^{33} \) erg s\(^{-1}\) (the range corresponds to an X-ray bolometric correction of 7–20), a factor of \( \sim 3000 - 8000 \). Unless the plasma density has been overestimated by 3–4 orders of magnitude, we are forced to conclude that either \( \eta \ll 0.1 \) or \( M \ll M_B \). Both, in fact, may hold naturally in globular clusters, given their low gas content.

Optically thin advection-dominated accretion flows (ADAFs; for a general overview, see Narayan, Mahadevan, & Quataert 1998), which are radiatively inefficient, are thought to develop when accretion rates drop below a critical threshold of \( \dot{M}_{\text{crit}} \approx \alpha^2 \dot{M}_{\text{Edd}} \approx 0.1 \dot{M}_{\text{Edd}} \), where the Eddington accretion rate is defined by \( \dot{M}_{\text{Edd}} = (\eta/0.1) \dot{M}_{\text{Edd}} c^2 \) and the Shakura & Sunyaev (1973) viscosity parameter is taken to be \( \alpha \approx 0.3 \) (Narayan et al. 1998). From the above estimate of the Bondi accretion rate, \( \dot{M}_B \approx 10^{-4} \dot{M}_{\text{Edd}} \), and so an ADAF, or some variant thereof (see Quataert 2001 for a review of the recent modifications of the basic ADAF model that incorporate the effects of outflows and convection), very likely exists in M15. We believe this accounts for the extraordinary quiescence of its nucleus, should it truly host a central massive BH. Similar arguments have been advanced to explain the dimness of supermassive (\( \sim 10^6 - 10^9 \) \( M_\odot \)) BHs in the nuclei of nearby giant elliptical (e.g., Fabian & Rees 1995; Mahadevan 1997) and spiral (Ho 2003) galaxies.

While accretion flows in globular clusters are expected to be radiatively inefficient, how low can \( \eta \) be? Is \( \eta \lesssim 10^{-4} \) possible? This issue is not yet well understood theoretically, as it depends on the currently uncertain physics of particle heating and acceleration (Quataert 2001). One can allow higher values of \( \eta \) by reducing \( M \) below the Bondi rate. Recent Chandra studies of elliptical galaxies find that their cores often accrete significantly below theBondi rate (e.g., Loewenstein et al. 2001; Ho et al. 2003). The accretion rate is thought to be curtailed by dynamical processes inherent to radiatively inefficient flows, which have the propensity to develop outflows (Blandford & Begelman 1999) and convection (Narayan, Igumenshchev, & Abramowicz 2000; Quataert & Gruzinov 2000; Igumenshchev & Narayan 2002).

Following Grindlay et al. (2001), we can turn the problem around and use the X-ray null detection to place an upper limit on the mass of the central BH. Assuming again that the BH accretes at the full Bondi rate and that \( \eta = 10^{-4} \), the upper limit on the bolometric luminosity translates into an upper limit of \( \sim 600 - 1000 M_\odot \) for the central BH.

4. SUMMARY

We use a sensitive, high-resolution Chandra image to place a stringent upper limit on the accretion luminosity of the nucleus of the globular cluster M15, which plausibly hosts a massive (~2000 \( M_\odot \)) BH. The bolometric luminosity of the nucleus is less than (2–4) \times 10^{-8} \text{ of the Eddington luminosity of the BH}. If the central BH accretes via a standard optically thick, geometrically thin disk at the Bondi rate, which we calculate from the electron density of the intracluster ionized plasma derived from pulsar dispersion measures, the nucleus should be \( \sim 3 - 4 \) orders of magnitude more luminous than observed. Unless the accretion rate has been severely overestimated, this fundamental inconsistency leads to the conclusion that the accretion process in M15 must be extremely radiatively inefficient, as theoretically predicted in the context of advection-dominated accretion flows or related models. The constraint on the radiative efficiency is not yet precise, however, because of the uncertain influence of outflows or convection on the accretion rate. Of course, the lack of an X-ray nucleus in M15 in itself can be taken as evidence that it does not contain a massive BH. This interpretation remains viable until the nature of its central dark mass concentration can be established with greater certainty.

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