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A 20 THOUSAND SOLAR MASS BLACK HOLE IN THE STELLAR CLUSTER G1[1]

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ABSTRACT

We present the detection of a $2.0(+1.4,-0.8)\times10^4\ M_\odot$ black hole (BH) in the stellar cluster G1 (Mayall II), based on data taken with the Space Telescope Imaging Spectrograph onboard the *Hubble Space Telescope*. G1 is one of the most massive stellar clusters in M31. The central velocity dispersion (25 km s^{-1}) and the measured BH mass of G1 places it on a linear extrapolation of the correlation between BH mass and bulge velocity dispersion established for nearby galaxies. The detection of a BH in this low-mass stellar system suggests that (1) the most likely candidates for seed massive BHs come from stellar clusters, (2) there is a direct link between massive stellar clusters and normal galaxies, and (3) the formation process of both bulges and massive clusters is similar due to their concordance in the $M_\bullet-\sigma$ relation. Globular clusters in our Galaxy should be searched for central BHs.

Subject headings: galaxies: individual (M31) — galaxies: star clusters — globular clusters: general — globular clusters: individual (Mayall II = G1)

1. INTRODUCTION

The questions of how the nuclei of galaxies form and why they contain massive black holes (BHs) remain unsolved. However, the recent discovery of a tight correlation between central black hole (BH) mass and bulge velocity dispersion (hereafter the $M_\bullet-\sigma$ relation; Gebhardt et al. 2000b; Ferrarese & Merritt 2000) does shed some light on the evolutionary history of massive BHs and their host galaxies. Many theories (e.g., Silk & Rees 1998; Haehnelt & Kauffmann 2000; Ostriker 2000; Adams, Graff, & Richstone 2001) predict such a correlation, and the exact details (i.e., slope and normalization) can discriminate among the various models. Presently, however, the data are inadequate to do this. One difficulty is that the galaxies studied so far have limited coverage in parameter space. There are not enough observations at the low-dispersion end, and yet this region provides the tightest constraints on determining both the slope and offset. The main reason for this lack of low-dispersion systems is that there are few that the *Hubble Space Telescope (HST)* can reasonably observe.

Due to their high central densities and proximity, globular clusters provide an alternative to studying galaxies to explore the low mass end. Furthermore, there is evidence that at least some globular clusters may be nuclei of accreted galaxies (Freeman 1993, Ferguson et al. 2002), and thus may contain central black holes if all galaxies contain them (Magorrian et al. 1998). The clusters G1 (Mayall II) in M31 and M15 are excellent objects for these studies. They both have high central densities and short central relaxation times (10^7 years for M15 and 10^8 for G1). Gebhardt et al. (2000c), van der Marel et al. (2002) and Gerssen et al. (2002) present results for M15 showing that it likely contains a central BH of a few thousand solar masses. If large (nonstellar) BHs exist in these stellar clusters, which have low escape velocities and apparently lack dark halos, they will pose a severe challenge to nearly every theory for the formation of massive BHs.

The cluster G1 lies 40 kpc from the nucleus of M31, projected approximately on its major axis. It is the most luminous stellar cluster in the Local Group and has a higher central surface brightness than any Galactic globular cluster. Djorgovski et al. (1997) report a velocity dispersion of 25 km s^{-1} from ground-based spectroscopy, and Meylan et al. (2001) derive a total mass of $(7-17)\times10^6 M_\odot$, with the uncertainty due to their lacking a velocity dispersion profile. To place G1 among Galactic globular clusters, we note that the compilation of Trager, Djorgovski, & King (1995) gives no cluster with central surface brightness $< 14.5\ V$ mag arcsec^{-2}, fully one magnitude fainter than G1 (Rich et al. 1996). NGC 5139 (ω Cen) is about as massive and luminous as G1, but its central surface brightness is 16.8 mag arcsec^{-2}. The highest measured velocity dispersion for any Galactic globular cluster is 18 km s^{-1}, for NGC 6441 and NGC 6388 (Pryor & Meylan 1993). It is interesting to note that both G1 (Meylan et al. 2001; Ferguson et al. 2002) and ω Cen (Freeman 1993) are possibly nuclei of accreted galaxies.

The high luminosity and remarkable central surface brightness of G1 led us to propose to obtain STIS spectroscopy of its nucleus (GO-9099; PI: Rich). This *Letter* reports the discovery of a $2.0\times10^4 M_\odot$ BH in G1. Analysis of central population gradients and detailed ground-based spectra will be reported in a future paper (Rich et al. 2003).

2. DATA

2.1. *STIS Observations*

We observed G1 using the Space Telescope Imaging Spectrograph (STIS) with the G750M grating and the $0.1''\times52''$ slit on 2001 November 1 UT. The position angle of the slit was 95°; since the major axis of the cluster is at 120° (Meylan et al. 2001), the slit ran along an angle 25° up from the major axis. The spectra cover 8276–8843 Å with 0.554 Å (19 km s^{-1}) per pixel and a resolution of FWHM = 1.06 Å or 37 km s^{-1}. The total integration time was 7.06 hr, divided into 20 exposures over two visits. We dithered along the slit to aid in the removal of cosmic rays and hot pixels. The dithering ranged between $\pm1''$, with non-integer steps. These large dithers allow us to make a

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hot pixel map directly from the data; this step is important because the hot pixels change during every orbit, and, to ensure the best quality map, it is ideal to use a hot-pixel map made from the data. The procedure for making this map involves iterations whereby we make an initial two-dimensional galaxy image that we subtract from the individual images, which then are used to make a new hot-pixel map. Five iterations are adequate to produce an accurate map. Pinkney et al. (2002) describe this procedure in more detail.

We use contemporaneous flat images taken during each orbit to correct for the pixel-to-pixel gain variation and fringing at these red wavelengths. The flat images are stable over many months and provide flat-field correction to better than a percent.

2.2. *Kinematics*

We are able to obtain kinematics out to $\pm 1\farcs1$. The modeling described below utilizes the velocity profile directly. However, for comparison with other work, Figure 1 plots the first two moments of a Gauss-Hermite polynomial expansion. The estimate of the velocity profiles relies on a non-parametric penalized maximum-likelihood technique, which is described in Gebhardt etal (2000a) and Pinkney et al. (2002). For the modeling, we use a symmetrized version of the kinematics (solid lines in Fig. 1), which increases the signal-to-noise for the estimate of the velocity profile. Sampling noise in the dispersion estimate—which can hamper measurements in Galactic clusters (Dubath et al. 1997)—is not significant for G1. The central STIS pixel ($0\farcs05 \times 0\farcs1$) contains about $10^4 M_\odot$ in stars projected into it, or 3000 $L_\odot$. If only giant stars contributed light, which provides the extreme situation, the central pixel would contain 30–100 stars, which is adequate to overcome sampling noise.

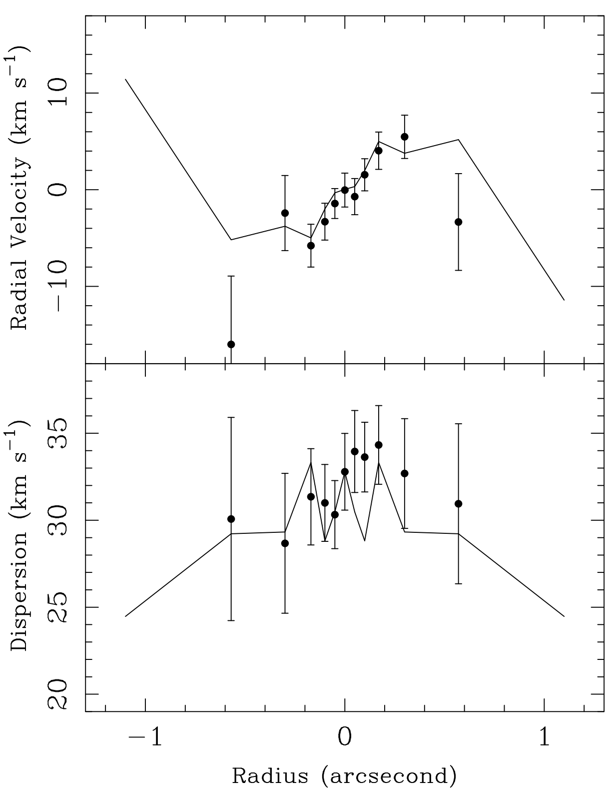

FIG. 1.— Radial velocity and velocity dispersion profile of G1 from the STIS observations. The points and the uncertainties come from the unsymmetrized measurements. The solid lines come from the symmetrized estimate that are used in the dynamical modeling. There is a single ground-based estimate of the dispersion that is not shown here; Djorgovski et al. (1997) measure $\sigma = 25.1 \pm 1.7$ km s^{-1} in a $1\farcs2 \times 3\farcs0$ aperture.

2.3. *Photometry*

We use the images as described in Rich et al. (1996). The surface brightness profile at large radii ($r > 0\farcs3$) is well measured using either the data from Rich et al. or Meylan et al. (2001). However, in the central regions of G1, many of the exposure where saturated, and we have to rely on the shorter exposures from Rich et al. (1996). These exposures consist of two 40 s exposures in both the F555W and F814W filter. In both of these, the center is well below the saturation limit. Unfortunately, these images where not dithered and so we cannot reconstruct higher spatially sampled data directly. We do not use deconvolved images for this analysis. Deconvolution techniques accurately recover the intrinsic surface brightness profile (Lauer et al. 1998), but the lumpiness of the G1 image, due to bright giant stars, may add significant noise to the deconvolution. Such artifacts can be understood using simulations, but for this initial analysis we rely on the observed images only using the profile from Meylan et al. Since the deconvolution will tend to make the observed profile steeper, models using a deconvolved profile will likely not change the best-fit BH mass but will make the uncertainties smaller. Thus, we conservatively use the observed profile.

We deproject the surface brightness profile to obtain the luminosity density using a direct inversion of the Abel integral (Gebhardt et al. 1996). We assume a minor-to-major axis ratio of 0.75 that is constant as a function of radius. This spheroidal distribution adequately represents the configuration of G1 as measured by Meylan et al. (2001). Changes in the assumed flattening have little effect on the results below.

3. MODELS

The models are similar to those presented in Gebhardt et al. (2002). They are axisymmetric, orbit-based models and so do not rely on a specified form for the distribution function. Thus, for an axisymmetric system, these models provide the most general solution. The models require an input potential, in which we run a set of stellar orbits covering the available phase space. We find a non-negative set of orbital weights that best matches both the photometry and kinematics to provide an overall χ^2 fit. We vary the central black hole mass and re-fit.

The orbit-based models store the kinematic and photometric results in both spatial and velocity bins. For G1, we use 12 radial, 4 angular, and 13 velocity bins. The data consist of the seven different STIS positions along a position angle 25° up from the major axis and one ground-based observation centered on the cluster. The point-spread function for both *HST* and ground-based observations are included directly into the models. The program matches the luminosity density everywhere throughout the cluster to better than 0.5%. The quality of the fit is determined from the match to the velocity profiles. The data points consist of 7×13 STIS velocity bins plus the one ground-based dispersion, making 92 total points. However, many of these points are correlated since the smoothing used for the velocity profile extraction tends to correlate adjacent bins. The reduction in the number of independent parameters is hard to estimate but is generally around a factor of 2–4 (Gebhardt et al. 2002).

Figure 2 plots a two-dimensional map of the different models and the corresponding contours for χ^2. The smallest value of χ^2 is 17; given the 92 parameters, the reduction of the independent parameters is about a factor of 5, higher than typical, which we attribute to the small radial extent of the data. The two independent parameters in the models are the BH mass and the stellar mass-to-light ratio (M/L). The best-fit BH mass is $2.0(+1.4,-0.8)\times 10^4 M_\odot$ with M/L_V = 2.6. Figure 3 shows the one-dimensional plot of χ^2 versus BH mass. The difference in χ^2 between the zero BH mass model and the best fit is 3.0, implying a significance above 90% for the BH detection.

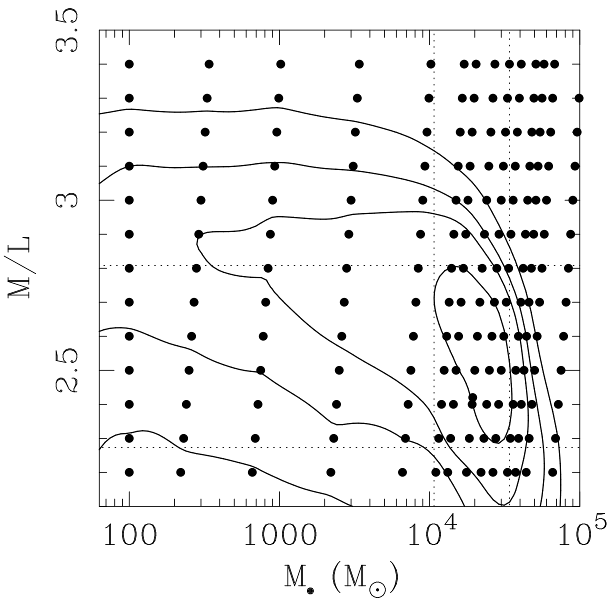

FIG. 2.— Two-dimensional plot of χ^2 as a function of BH mass and M/L for G1. The points represent models that we actually ran. The contours were determined by a two-dimensional smoothing spline interpolated from these models, and represent $\Delta\chi^2$ of 1.0, 2.71, 4.0, and 6.63 (68%, 90%, 95%, 99% in projection). The vertical lines are the 68% limit for the BH mass, and the horizontal lines are the 68% limit for M/L.

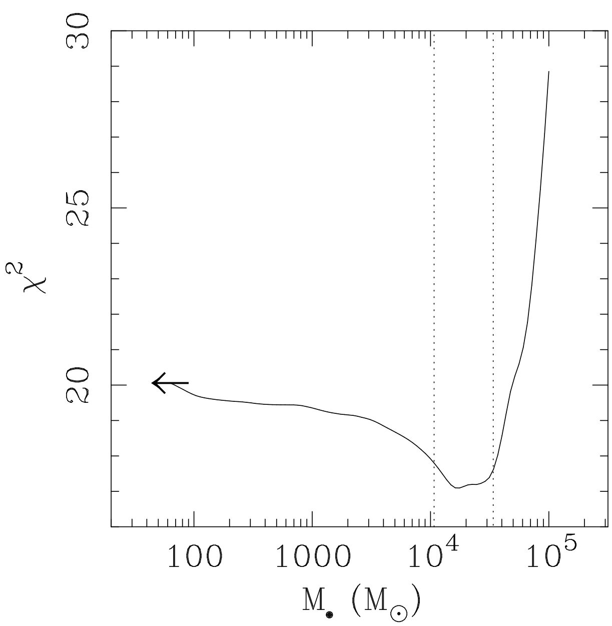

FIG. 3.— χ^2 as a function of BH mass. We have marginalized over M/L. The vertical dashed lines denote the 68% confidence band quoted for the BH mass uncertainties. The arrow on the leftmost point indicates that this point is actually at zero BH mass, off the edge of the panel.

4. RESULTS

Our best-fit model has a BH mass of $2.0\times 10^4 M_\odot$. We can place this measurement on the $M_\bullet - \sigma$ relation (Gebhardt et al. 2000b; Ferrarese & Merritt 2000) using the ground-based measurement of $\sigma = 25.1 \pm 1.7$ km s^{-1}. Figure 4 plots the $M_\bullet - \sigma$ correlation for nearby galaxies using the compilation and the linear relation given in Tremaine et al. (2002). G1 lies in excellent agreement with the extrapolation of the linear fit to the local galaxies.

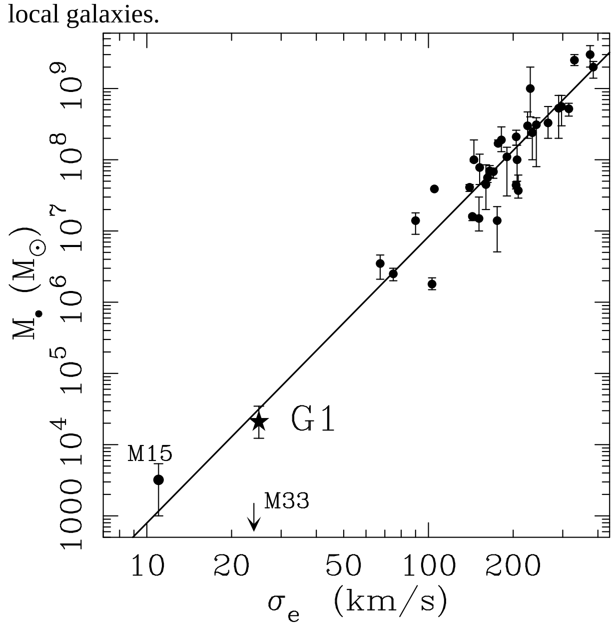

FIG. 4.— The $M_\bullet - \sigma$ correlation for nearby galaxies, adapted from Tremaine et al. (2002). We include here the upper limit for M33 (Gebhardt et al. 2001), the BH mass estimate for the globular cluster M15 (van der Marel et al. 2002 and Gerssen et al. 2002), and the mass for G1. The solid line is the linear fit given by Tremaine et al., which does not include the cluster G1 or M15.

5. DISCUSSION AND CONCLUSIONS

G1 has traditionally been called a globular cluster. However, Meylan et al. (2001) offer the hypothesis that it is a nucleus of an accreted small galaxy, similar to NGC 205. Furthermore, Ferguson et al. (2002) report the discovery of a disrupted galaxy near G1, speculating that the two may have been part of the same system. A similar origin for ω Cen has been proposed by Freeman (1993). Evidence in favor of this interpretation for both clusters include their large spread in metallicity and their exceptionally large velocity dispersions relative to most globular clusters. If G1 is the nucleus of an accreted galaxy, and if all bulge systems have BHs in their centers (Magorrian et al. 1998), then, to the extent that a massive, bound cluster can be viewed as a "mini-bulge," it is no surprise that G1 has a BH as well. Combined with the results for M15, it may be that *every* dense stellar system hosts a central BH.

There are significant consequences for these small systems having central BHs. First, it provides a direct link between stellar clusters and galaxies. Galaxy correlation studies that include globular clusters (Burstein et al. 1997, Geha et al. 2002) show that they typically lie near to, but slightly offset from, the correlations for the nearby galaxies. However, the large scatter prevents a definitive comparison. The tightness of the $M_\bullet - \sigma$ relation allows us to explore their connection in better detail. The current results show that there is little difference between the smallest and largest dense stellar systems.

Second, the existence of large (nonstellar) BHs in these small systems constrains BH formation models. The low escape velocity of M15 and G1 (<100 km s^{-1}) makes it difficult to grow a BH slowly over time. Growing black holes from adiabatic accretion of gas is difficult since globular clusters have a hard time holding onto any gas (namely that from mass loss in evolved stars) due to their low escape velocities. If BHs are grown from accretion of stars and stellar remnants, the cluster must be able overcome the large recoil velocities due to two-body interaction near the center. A possible solution to this dilemma is to have a large initial seed mass for the BH that cannot subsequently get ejected from two-body interactions. Miller & Hamilton (2002) and Portegies Zwart & McMillan (2002) discuss a mechanism in which massive BHs can exist in globular clusters.

Third, one of the more important aspects of theories for the formation of supermassive BHs in galaxies is that each has to start with a seed BH. There are multiple explanations as to where these seeds come from; whether they are primordial, created during the formation of the galaxy, or formed in subsequent evolution is unknown. If small stellar clusters contain BHs, due to their ages, they are a natural candidate for the formation sites of seed BHs. A stellar cluster that formed before the host protogalaxy collapsed could have easily donated its BH to the galaxy center. All of the theoretical models require only a modest-sized BH to act as a seed, around $1\times10^4 M_{\odot}$ or less.

As an interesting counterexample, the galaxy M33 appears not to have a BH. Gebhardt et al. (2001) measure an upper limit of $1500M_{\odot}$. The main difference between M33 and other galaxies with detected BHs is that M33 does not have a a clear bulge component. However, M33 does have a compact nucleus, whose stellar density is as high as those in globular clusters. Thus, if any dense cluster has a BH then it is puzzling that M33's nucleus has none. There are no obvious reasons for this difference. However, M33's nucleus has a very different age than G1; the former contains a significant population of stars younger than a few Gyr (e.g., O'Connell 1983), whereas the latter is older than 10 Gyr (Meylan et al. 2001). It is possible that either conditions to make a massive BH were better in the past (i.e., different initial mass function) or that M33's nucleus has not had enough time to create one. In any event, we need more data on a larger set of nuclei and clusters in order to explore this issue.

The model that we use for G1 assumes a constant stellar mass-to-light ratio. The relaxation time for G1 near the center is short and we expect heavy remnants there. By not including them, we overestimate the BH mass. We estimate the effect by extrapolation of the Fokker-Plank simulations of Dull et al. (1997) for M15. They find that $\sim 1000 M_{\odot}$ of remnants is in the central regions of that cluster (see discussion in Gerssen et al. 2002). G1 is $\sim$5 times more massive than M15, implying that it has 5 times more remnants given the same initial mass function. However, the relaxation times are significantly longer in G1 (about a factor of ten), suggesting that the presence of heavy remnants is even less of a problem. Furthermore, Gerssen et al. include models which incorporate the appropriate mass-to-light variation and find that the required black hole mass *increases* slightly. The reason is that even though the remnants increase the mass-to-light ratio at the smallest radius, the giant star cause it to drop towards the center since they are centrally-concentrated. This drop in mass-to-light balances the increase from the heavy remnants, thereby causing litle effect on the BH mass.

A possible concern comes from comparing the *HST*/STIS dispersions with that measured from the ground using different setups and analysis. Therefore, we also ran models in which we use only the *HST* data. We find essentially the same BH mass, but the confidence band decreases slightly. The difference in χ^2 between the no-BH mass model and the best fit changes from 3.0 to 2.5. We find no reason to suspect that either dispersion measurement is biased and use both in the dynamical models.

The dynamical constraints for G1 can be improved with more extensive ground-based kinematic observations (i.e., multiple position angles). In addition to G1 and M15, there are a significant number of globular clusters that can be exploited for these studies. Moreover, ground-based observations should have sufficient spatial resolution to measure a central BH. The most important challenge, however, lies in understanding the contribution of heavy remnants. As explained above, the impact of heavy remnants on G1 should not be severe because of its long relaxation time, but more quantitative estimates of this effect using evolutionary models would be highly desirable. Based on experiments done so far in Gerssen et al. (2002), it appears that the BH mass estimates in M15 and G1 are unbiased.

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