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The Central Mass Concentration in M15

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Abstract
We have obtained stellar absorption line spectra with STIS to measure the radial velocities of individual stars in the crowded center of the globular cluster M15. These data increase the number of stars with known radial velocities within the central arcsec by a factor of about three and significantly improve the constraints on the mass distribution in M15. The data provide the most detailed look of the central structure of any globular cluster and show that there is a compact dark central mass component. Whether this is due to an intermediate mass black hole or to normal mass segregation cannot yet be uniquely established. However, the former does provide a plausible interpretation of the data. If there is indeed a black hole, its mass is consistent with the relation between velocity dispersion and black hole mass that has been established for galaxies.

1.1 Introduction

The remarkably high stellar density in the center of M15 has prompted numerous studies to explore this region in more detail. Star count profiles derived from *HST* data of M15 are consistent with both the predictions of Fokker-Planck models and with stars orbiting around a central dark mass concentration. Photometry alone cannot establish whether mass follows light and kinematical studies are therefore required to constrain the central mass distribution.

The high central densities in the cores of globular clusters lead to significant blending of light from neighboring stars. With seeing limited observations from the ground it is therefore difficult to unambiguously measure the radial velocities of individual stars in the very center of M15. To counter this problem, we have used the STIS spectrograph on *HST* to obtain spectra of individual stars in the center of M15 using the highest spatial resolution that is currently attainable. These data minimize blending, but cannot completely remove it. However, from WFPC2 photometry we were able to quantify the blending and subsequently correct for it.

In galaxies, stellar velocities are usually derived from integrated light spectra. In globular cluster however, the few brightest stars in an aperture will dominate the integrated light, complicating the interpretation of the results. Stellar motions can also be derived from images obtained over a sufficiently long time line. Such proper motion studies have the added benefit that they provide two of the three components of stellar motion. However, in the very crowded central regions of globular clusters the method is difficult to apply. The most straightforward method to constrain the central masses in globular clusters is therefore to determine the radial velocities of individual stars.

1.2 Data

We have used the Space Telescope Imaging Spectrograph on board of HST to obtain long slit stellar absorption line spectra of the center of M15. STIS is a long slit spectrograph and in order to map a two-dimensional region we placed the slit at 18 adjacent positions as shown schematically in Fig. 1.1. The slit width is 0.1 arcsec and the observations therefore cover the central two arcsec of M15.

All spectra were centered around the Mg b absorption line feature and have a velocity scale of 16 km s^{-1} per pixel. The expected central velocity dispersion in M15 is $\sim$ 12 km s^{-1}. Several intricate corrections for the motion of *HST* and the exact location of each star with respect to slit were therefore necessary (van der Marel et al. 2002) since both can introduce errors that are as large the expected central velocity dispersion. The radial velocities were derived by cross-correlating the STIS spectra with Kurucz model templates. In the end we were able to reliably measure the radial velocities for 64 stars in the STIS data. Within the central arcsec the STIS data triple the number of stars with measured radial velocities. About one third of the STIS stars already have a ground based measurement of the radial velocity. A comparison between the two velocity sets shows that the STIS velocities are accurate in a systematic sense to about 2.5 km s^{-1}. The residuals between the STIS data and the ground based data show no trends with either stellar magnitude or color. The mean residual velocity is 0.2 km s^{-1}.

The central velocity dispersion in M15 derived from the STIS data is 14 km s^{-1} which is somewhat higher than the previously determined ground based value of about $\sim$ 12 km s^{-1}. Rather than to use this value directly we use a model approach to constrain the central mass density in M15. In order to compare the models to the data over the largest range in radii possible, we combine the STIS data with a compilation of ground based velocities. The combined data set consists of 1797 stars covering radii from 0.3 to 1000 arcsec.

1.3 Models

Stellar velocity profiles are estimated from the discrete data set using a nonparametric technique. The projected RMS ($v^2+\sigma^2$ averaged over rings on the sky) velocity profile and its 1σ uncertainties are shown in the right panels of Fig. 1.1. These profiles allow a visual comparison between the data and the models. The actual quantitative comparison between the models and the data is made by calculating the likelihood of each model given all 1797 measured radial velocities. To determine the mass distribution in M15 we assume that the cluster is spherical and that it is in hydrostatic equilibrium. Such a system obeys the Jeans equation (Binney & Tremaine 1987). In order to solve this equation for velocities we require the mass density and the gravitational potential. We obtain the luminosity density by deprojecting a combination of the surface brightness profiles published by Trager et al. (1995) and Guhathakurta et al. (1996) and transform this into a mass density by assuming either a constant mass-to-light ratio (Υ) or an Υ profile based on Fokker-Planck models. The gravitational potential is obtained from the mass density using Poisson's equation. The contribution of a possible central point mass $M_{\rm BH}$ is added to the potential. With both the

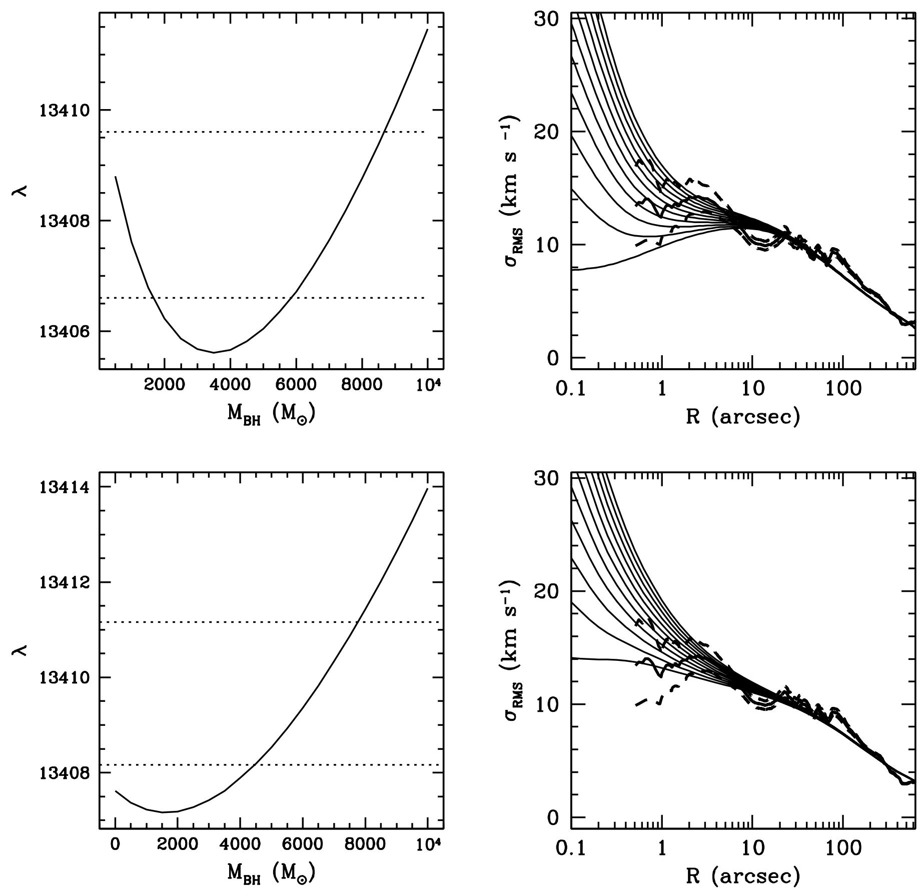

Fig. 1.1. Comparisons between the STIS data and model predictions. The top two panels show the results for a model with a constant mass-to-light ratio. The bottom panels are for a model in which the mass-to-light profile based on the Fokker-Planck models of D97 has been used. Models with a central black hole ranging from 0 to $10 \times 10^3 M_\odot$ are shown in the right panels. A nonparametric estimate of the projected RMS velocity profile is overplotted with the heavy line (heavy dashed lines are 68% confidence regions). The left panels show the likelihood of each model given the data. The best-fit models (minimum λ) have a $M_{\rm BH}$ of 3500 $M_\odot$ and 1700 $M_\odot$ respectively. The dotted lines indicate the 1σ and 2σ confidence levels.

mass density and the gravitational potential determined we can solve the Jeans equation for velocities and project the results along the line of sight.

1.3.1 Constant mass-to-light ratio

The first set of isotropic models that we calculate have Υ independent of radius. The top left panel in Fig. 1.1. shows the likelihood values as a function of point mass $M_{\rm BH}$.

The best-fitting mass-to-light ratio is fairly independent of $M_{\rm BH}$, $\Upsilon = 1.6 \pm 0.1$. The best-fit $M_{\rm BH} = (3.2 \pm 2.2) \times 10^3\ M_\odot$. To quantify the effects of uncertainties in the cluster position (about 0.2 arcsec) on the mass $M_{\rm BH}$ we repeated the likelihood analysis with the M15 center shifted to different positions by several tenths of arcsec. The resulting changes in $M_{\rm BH}$ are insignificant, less than 10 percent.

1.3.2 *Varying mass-to-light ratio*

While a constant mass-to-light profile model is a useful benchmark, it is an oversimplification in the cores of globular clusters. Globular cluster evolution is driven by two-body relaxation. The lack of a constant density core in M15 suggests that this cluster has undergone core collapse as a result of this process. A natural consequence of two-body relaxation is mass segregation. In an attempt to reach equipartition, heavy stars and dark stellar remnants sink to the center of cluster, which causes a central increase in $\Upsilon(r)$. This boosts the predicted velocities close to the center, which may obviate the need to invoke a central black hole in the models.

Detailed Fokker-Planck calculations are required to determine mass-to-light profiles for M15. We have not calculated such model ourselves. Instead, we relied on the results published by Dull et al (1997, hereafter D97 *). We calculated isotropic models with the mass-to-light profile of D97. The bottom two panels of Fig. 1.1 show that models without a black hole are found to be statistically acceptable (within 1σ) although inclusion of an intermediate-mass BH, with $M_{\rm BH} = 1.7^{+2.7}_{-1.7} \times 10^3\ M_\odot$, still provides a marginally better fit to the data (although not a statistically significant one).

An important shortcoming of the D97 model is that it assumes that all neutron stars that are formed in the cluster are retained. The same is true for N-body models constructed recently by Baumgardt et al. (2003). However, the observed distribution of pulsar kick velocities indicates that the retention factor should be no more than 10 percent (Pfahl et al. 2002). In this sense, the D97 models therefore only provide an upper limit on the concentration of dark remnants in M15. More realistic evolutionary models that include neutron star escape will conceivably require a more massive and statistically significant black hole to fit the data. Alternatively, white dwarfs may be used to account for the central mass concentration. However, a white dwarf population will be less centrally concentrated than the more massive neutron stars and is not necessarily sufficient to fit the data at the smallest radii.

1.4 Summary

The *HST*/STIS data of M15 that we obtained provide the most detailed view of the central structure of any globular cluster to date. The data show that there in a dark central mass concentration in M15 but it is not uniquely established whether this is due to a central black hole or to normal mass segregation. It is interesting to note that independent evidence is emerging for central black holes in other globular clusters. Gebhardt et al (2002) recently found dynamical evidence for a black hole in in the globular cluster G1. The relaxation times in this cluster are longer than in M15 and it is therefore more difficult to explain the G1 data in terms of mass segregation.

* The authors of D97 recently discovered an error in their published mass-to-light ratio profile. Their published profile has a radius scale that is too compressed by a factor 2.82. The results presented here (as in Gerssen et al. 2003) use the corrected version of this profile and this yields a significantly lower $M_{\rm BH}$ than in Gerssen et al. (2002).

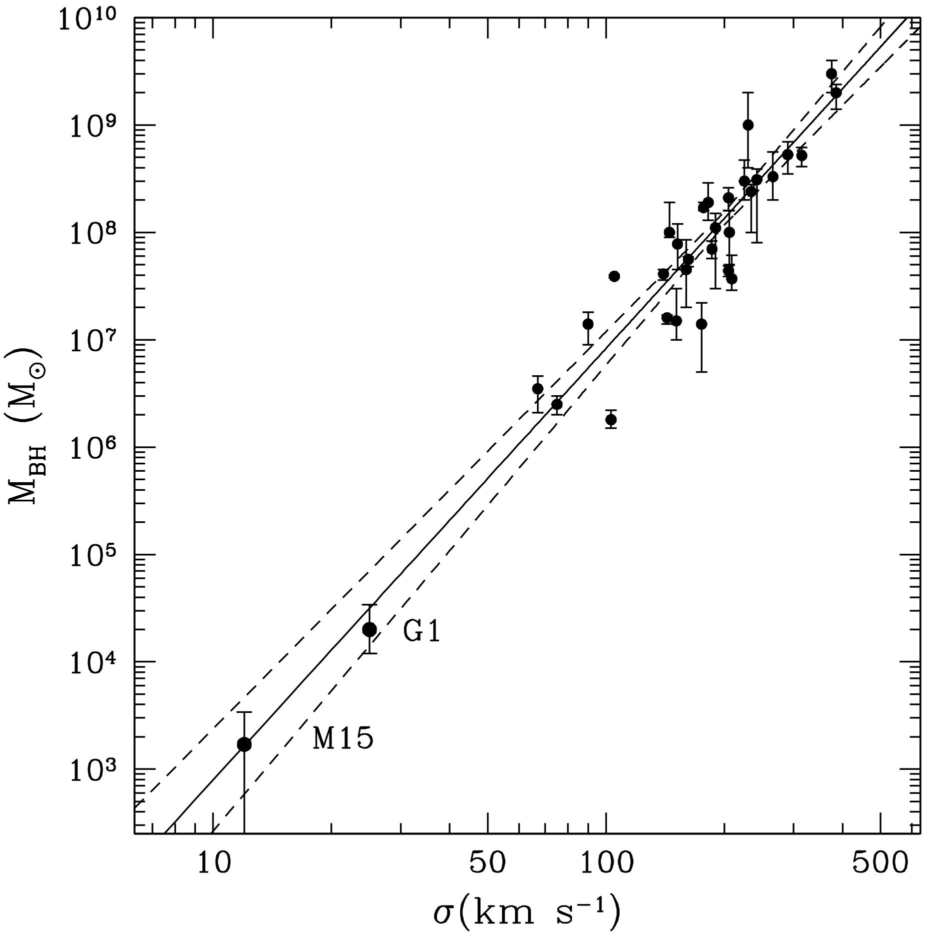

Fig. 1.2. The black hole mass versus velocity dispersion σ. solid points are measurements for various types of galaxies from the compilation of Tremaine et al. (2002). The solid line is the best linear fit and the dashed lines show the 1σ confidence band. Overplotted are the estimates for central black holes in the globular clusters M15 and G1.

Because of the somewhat unrealistic assumption of the neutron star retention in the models of D97 and because of the independent evidence for a black hole in the globular cluster G1, the presence of a black hole in M15 remains plausible. The best-fit black hole mass obtained with the (corrected) D97 mass-to-light profile and with the constant mass-to-light ratio assumption are both consistent with the correlation between velocity dispersion and black hole mass that has been inferred for galaxies (see Fig. 1.2 and Tremaine et al. 2002). This may suggest the possible existence of an important new link between the structure, evolution and formation of globular clusters, galaxies and their central black holes.

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