Measuring the Stellar Kinematics of the S0 Galaxy NGC 4203

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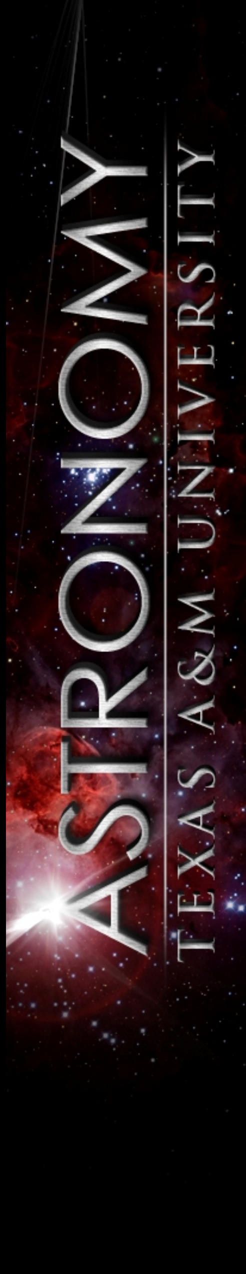

Abstract

Black holes (BHs) lie at the centers of every large galaxy, and their masses can be measured in two ways, by modeling the motions of stars or gas. Both methods suffer from different systematic effects, therefore comparisons between the two are important for assessing the consistency of the methods and the effects on the BH - host galaxy relations. However, there are only a few cases in which a galaxy's BH mass has been determined using both stellar and gas-dynamical methods. The nearby, S0 galaxy NGC 4203 provides the opportunity to conduct this necessary cross-check. Here we present near-infrared adaptive optics (AO) observations of NGC 4203 taken with the integral field spectrograph OSIRIS on the Keck II telescope. We measure the velocity, velocity dispersion, and higher-order velocity moments, h_3 and h_4, within ~100 pc of the galaxy's center. We find that the galaxy is rotating, and that there is a drop in velocity dispersion at the nucleus. The stellar kinematics on these small spatial scales are essential for a robust determination of the NGC 4203 BH mass, which can then be compared to a gas-dynamical determination from existing *Hubble Space Telescope* (*HST*) observations.

Introduction

The masses of central BHs are closely correlated with the large-scale properties of galaxies, such as the bulge luminosity and stellar velocity dispersion (e.g., Kormendy & Ho 2013, Saglia et al. 2016, van den Bosch 2016). Although the BH gravitationally influences only the innermost regions of galaxies, the BH mass is dependent on the global properties of the galaxy. This suggests that BHs and their host galaxies evolve together, with the growth of one affecting the growth of the other. Our understanding of the interplay between supermassive BHs and galaxies rests on reliable BH mass measurements.

Stellar and gas-dynamical modeling are the two main methods for measuring BH masses. The methods are independent of each other and suffer from their own systematic effects. Comparisons between the two techniques show stellar-dynamical BH mass measurements are a factor of 2-3 larger than gas-dynamical BH mass measurements (e.g., de Francesco et al. 2006, Rusli et al. 2011, Gebhardt et al. 2011, Walsh et al. 2012, Walsh et al. 2013, Barth et al. 2016), however there are very few galaxies with the necessary characteristics to carry out both methods effectively. More comparison studies are needed to evaluate the consistency of the methods and the impact on the BH scaling relations.

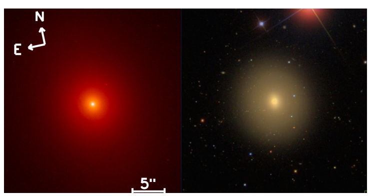

Figure 1. *HST*/Wide-Field Planetary Camera 2 F814W image of NGC 4203 (left) and Sloan Digital Sky Survey (SDSS) image (right) of NGC 4203. For the SDSS image, north is up and east is to the left, and each side is 390", or 28.5 kpc.

NGC 4203 is an S0 galaxy at a distance of 15.1 Mpc with a broad-lined active galactic nucleus (AGN). Previous studies have found an upper-limit on the BH mass of 5.2×10^7 - 1.3×10^8 $M_\odot$ (Sarzi et al. 2002, Beifiori et al. 2009) using *HST* observations of the gas kinematics at a single slit position. Additional *HST* spectroscopy at multiple slit positions have been obtained to constrain the gas-dynamical BH mass (GO-11571; PI Shields). NGC 4203 is also suitable for laser guide star AO observations from large, ground-based telescopes, and here we focus on measuring the stellar kinematics within the central ~100 pc. The stellar kinematics will later be modeled to infer the mass of the BH. Thus, NGC 4203 affords us the unique opportunity to compare this stellar-dynamical BH mass measurement to a gas-dynamical determination.

Observations

Data were taken on May 5-6, 2010 using the integral field spectrograph OSIRIS on the Keck II telescope with AO. We used the K broadband filter to cover 1.865 - 2.381 μm, the 0.05" spatial scale, and spent a total of 3.6 hours on-source observing the galaxy. The long-axis of OSIRIS was aligned with the galaxy major axis at a position angle of 10° east of north. Velocity template stars (K and M giants) were observed with OSIRIS in the same setup as well.

Method

From the OSIRIS observations of NGC 4203, we constructed 53 spatial bins to obtain spectra with a minimum S/N of 40. We measured the line-of-sight velocity distribution (LOSVD) by comparing template stars to the galaxy spectra using the penalized pixel fitting (pPXF) method (Cappellari et al. 2004). The LOSVD is given by the first four Gauss-Hermite moments (V, σ, h_3, h_4), where h_3 measures the LOSVD's asymmetric deviation from a Gaussian (skewness) and h_4 describes the distribution's symmetric deviation (kurtosis). Using pPXF, we fit over a wavelength range of 2.22-2.38 μm, which covers prominent absorption features like the CO bandheads, and included a first degree additive Legendre polynomial and a second degree multiplicative polynomial to account for the AGN and continuum shape differences between the template stars and galaxy spectra. Errors on the LOSVD parameters were calculated using a Monte Carlo simulation with 200 iterations. During each realization, we took the best-fit model spectrum and added random Gaussian noise to simulate an observed spectrum, then re-fit with pPXF.

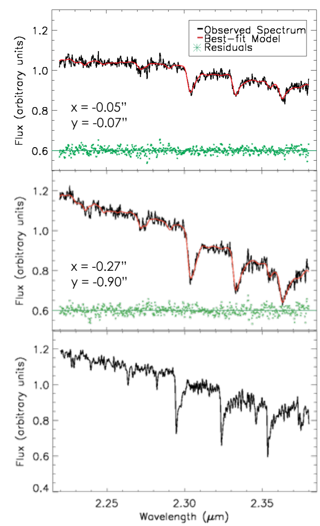

Figure 2. The top two panels are example fits to the NGC 4203 spectra at three different spatial locations. The black line represents the observed galaxy spectrum, the red line is the best-fit model from pPXF, and the green points are the residuals that have been shifted up by an arbitrary constant. The bottom panel is a spectrum of a K2 III star that dominated the optimal template used to measure the NGC 4203 stellar kinematics.

Results

The stellar kinematics are shown as a function of spatial location in Figure 3. We find that the galaxy is rotating, with velocities about ± 40 km/s, and that the velocity dispersion decreases from ~170 km/s at a radius of 1" to 110 km/s at the center. Typical uncertainties on the kinematics are 8 km/s, 10 km/s, 0.04, 0.05 for V, σ, h_3, and h_4, respectively.

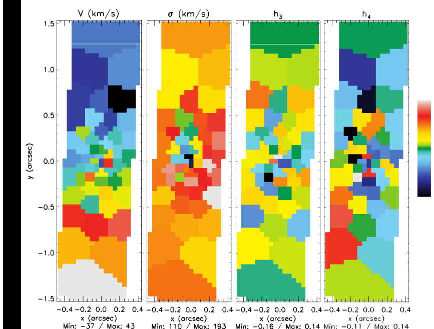

Figure 3. Maps of the NGC 4203 stellar kinematics. The velocity map shows that the galaxy is rotating, with the north side of the galaxy corresponding to blueshifted velocities. The velocity dispersion decreases at the nucleus compared to the outer spatial bins. There are no clear trends in the h_3 and h_4 maps. For NGC 4203, 1" corresponds to 73 pc.

The AGN in NGC 4203 makes measuring reliable stellar kinematics at the center difficult. We therefore generated a new set of spatial bins in which the three innermost lenslets showing AGN contamination were excluded. We also tested changing how the measurements were made with pPXF. We allowed the stars making up the optimal template to change between spatial bins, adjusted how the continuum was modeled through the use of different additive/multiplicative Legendre polynomials, tried other template libraries (Wallace & Hinkle 1996, Winge et al. 2009) after correcting for spectral resolution differences, and varied the wavelength range we fit over. All of the above tests produced consistent results as those plotted in Figure 3, and there continues to be a decrease in the stellar velocity dispersion at the nucleus. Such σ-drops are commonly found in spirals and in some early-type galaxies (e.g., Peletier et al. 2007, Lyubenova et al. 2008), and are often associated with a dynamically cold central stellar disk. Dynamical modeling is needed to determine the mass of the central BH.

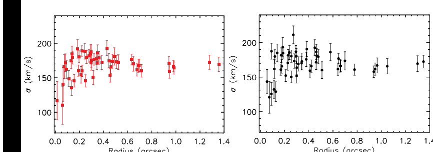

Figure 4. Plots of the velocity dispersion as a function of projected distance from the nucleus. We constructed spatial bins using all the OSIRIS data (left) and excluding the central spectra with clear AGN contamination (right). In both cases, there is a drop in the velocity dispersion at small radii.

Conclusion

Measuring stellar kinematics on small spatial scales is a crucial step in determining the mass of the BH at the center of NGC 4203. In this study, we have established a robust set of kinematics from integral field unit observations assisted by AO. NGC 4203 exhibits clear rotation and surprisingly the velocity dispersion decreases at the nucleus. The next step of the project involves measuring kinematics from seeing-limited, large-scale spectroscopy. All of the kinematics, along with information from imaging observations, will be fit with orbit-based dynamical models, leading to a secure stellar-dynamical BH mass determination that can be compared to a BH mass measurement from *HST* observations of the nuclear gas disk.

References

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Acknowledgments

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