The Black Hole Mass in NGC 4258 from Gas Kinematics[1]

David DeColibus and Jason Pinkney (Ohio Northern University)

[1]Based on observations made with the NASA/ESA Hubble Space Telescope operated by the AURA under NASA contract NAS 5-26555.

ABSTRACT

NGC 4258 (or M106) is an important galaxy for the demographics of supermassive black holes (SMBH). Radio (VLBA) observations of its nuclear disk of water masers has allowed a very precise estimate of the mass of the central SMBH (3.82 ± .01 × $10^7 M_\odot$), and the distance to the galaxy (7.6 Mpc). Hubble Space Telescope (HST) archival data allow the measurement of the BH mass in two additional, independent ways: stellar and gas kinematics, thus providing a crucial test of these more widely-used methods. Here we report on progress in a re-analysis of the archival data allowing gas kinematics. These data consist of HST long-slit spectroscopy from two programs, a total of 6 slit positions. We have fitted the Hα + [NII] and [SII] lines in order to determine radial velocities and velocity dispersions as a function of distance from the BH. The gas only shows organized rotation out to 0.4" . The Hα emission shows a broad-line (BL) component from the central AGN, and regions outside of the BL region show greater line widths than expected for a kinematically "cold" gas disk. We report initial results of modeling the kinematics as resulting from a thin, inclined disk of line-emitting gas orbiting under the influence of gravity only. Our best-fitting model has an M_{BH} of $2x10^7 M_\odot$.

MOTIVATION

NGC 4258 (also known as Messier 106) is a special galaxy because it has the most well defined black hole mass measurements of any galaxy besides our own. NGC 4258 is a type SABbc spiral galaxy, approximately 7.6 Mpc away. It has an active galactic nucleus, classified as a LINER Seyfert 1.9 AGN. Notably, NGC 4258 also has a sub-parsec scale molecular disk producing water masers which provide a precise estimate of the black hole mass with which to compare other techniques for BH mass measurement. The technique of stellar kinematics was already shown by the "Nuker" team (Siopis et al 2009) to give a consistent BH mass. This team and another led by D. Axon also obtained STIS spectroscopy allowing the gas kinematics technique. Pastorini et al (2007) analyzed these archival data and applied the gas kinematics technique, but we noticed an error in that work which has inspired our new analysis. Here we present preliminary results for only the 3 slit positions of the Axon dataset.

Fig. 1

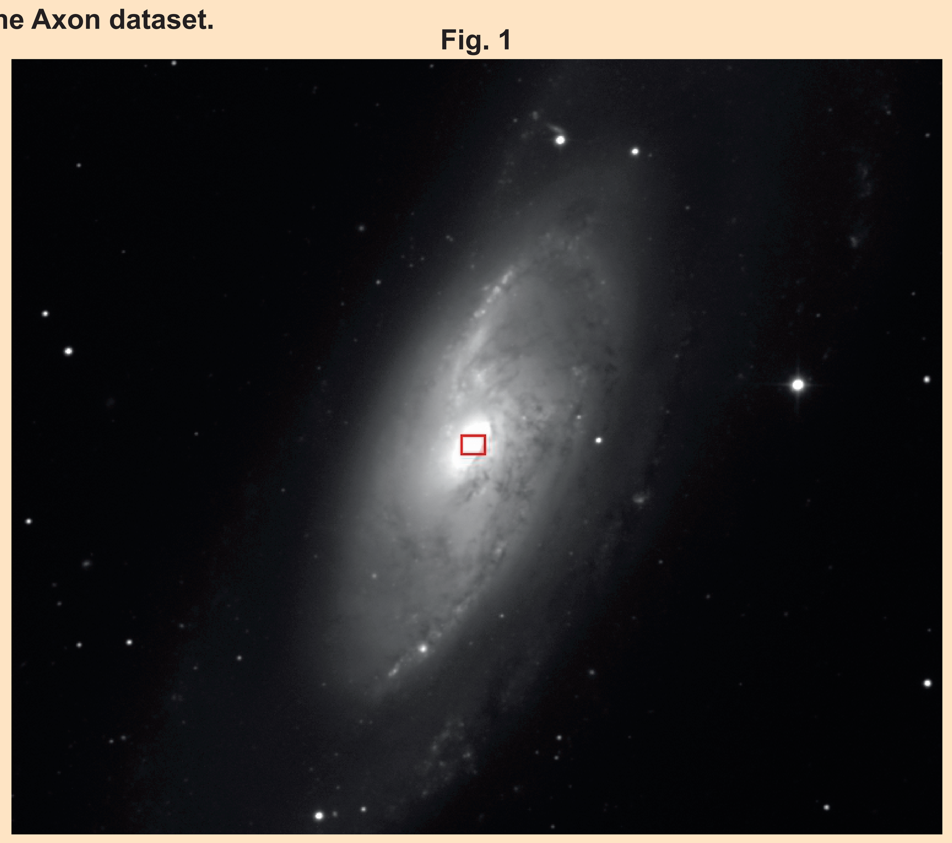


Fig. 1: NGC 4258 in R-band from ground-based observations. The red box shows the field of view of Fig. 4b.

OBSERVATIONS/DATA

All observations were taken using the Hubble Space Telescope.

IMAGING

- WFPC2, deconvolved, using the F547M and F656N filters.
- ACS (with WFC detector), with the F814W and F658N filters.
- Ground-based images: MDM Observatory, 1.3m + Echelle CCD in Johnson R-band
- NICMOS: NIC2, F160W filter

SPECTROSCOPY

- HST's STIS (Space Telescope Imaging Spectrograph) longslit spectrograph.
  - "Nuker" data: G750M @ 6581 Å, using 52x0.1" slit, 3 positions (omitted from this poster)
  - "Axon" data: G750M @ 6768 Å, using 52x0.2" slit, 3 positions
- Ground-based: MDM Observatory, 2.4-m + ModSpec longslit spectrograph.

Longslit Spectra

These figures show the spectrum of NGC 4258 around the Hα region. Fig. 2a is an example of the emission line fitting process, including some of our results. We fit Gaussians to five narrow emission lines (Hα, the two [NII] lines, and the two [SII] lines) and an independent broad-line Hα component. This particular spectrum is of the central pixel in the spectrum.

Fig. 2b is the normalized spectrum which is input into the program. The emission features are easily visible, and the broad-line (high velocity dispersion) component is obvious around the Hα region. This particular image has a wavelength range of 6490 to 7045 Å left to right. The black and white noise is an artifact of the normalization process, and does not affect our results.

Fig. 2a

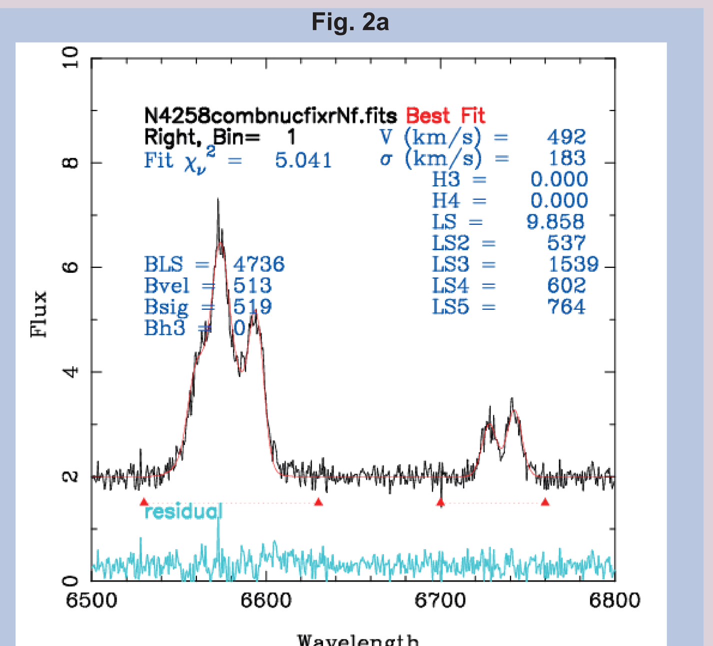
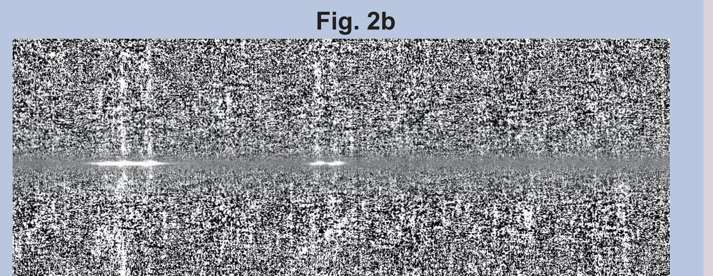


Fig. 2b



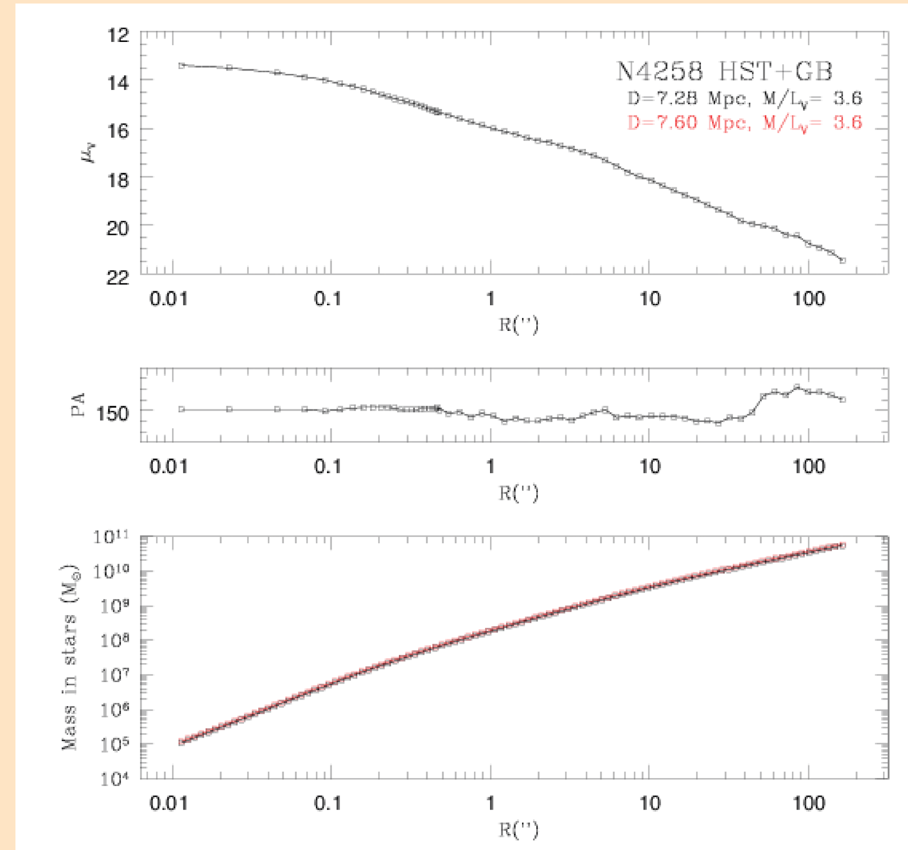
Radial Mass Distribution of Stars

The mass due to stars, gas, and dark matter must be subtracted from the total mass to determine the black hole mass.

The radial mass distribution can be derived from the surface brightness distribution obtained from high resolution (HST) imaging. The assumption is that the mass is proportional to the light (because more light means more stars). A mass-to-light ratio (M/L) must be adopted which takes into account the dark matter and gas present.

- Used non-parametric recovery of the luminosity distribution ala Gebhardt et al (1996)
- Used software npdyne (Gebhardt).
- Used M/L_V = 3.6 derived from stellar kinematics (Siopis et al 2009).

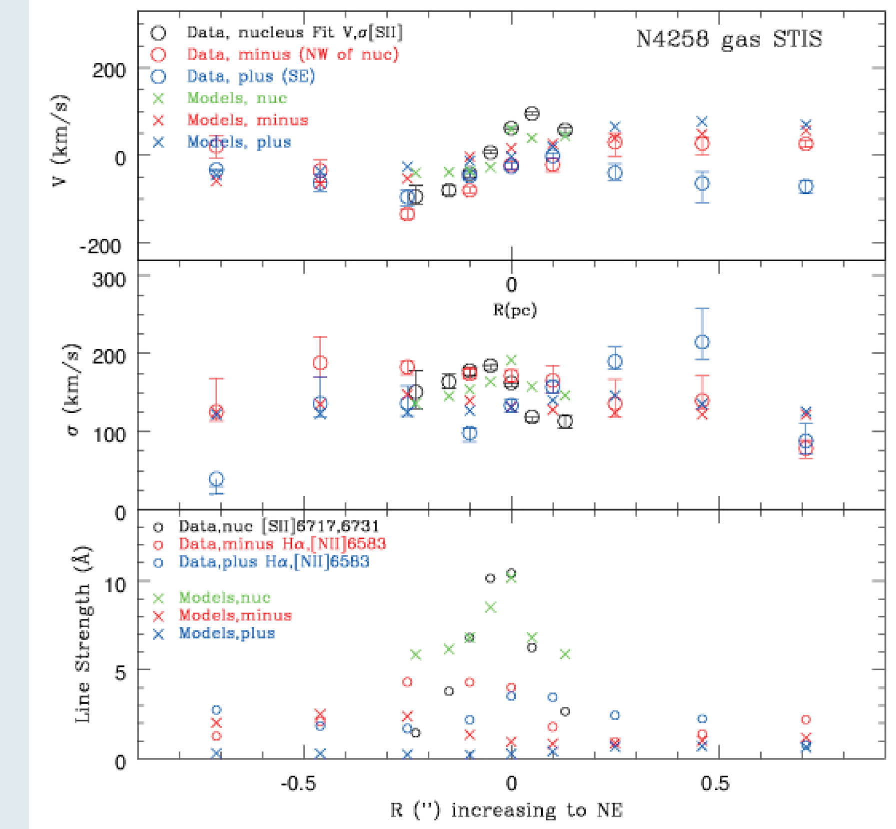
Fig. 3



Emission Line Kinematics: Data vs. Models

This figure shows a plot of our preliminary results from emission line and gas disk modeling using our three 52x0.2" slits. Our first slit was for the nucleus, using [SII] lines instead of the brighter Hα and [NII] lines due to the influence of broad-line emission. Our other slits were offset by -0.2" and +0.2", respectively, and were modeled using five lines- Hα, the two [NII] lines, and the two [SII] lines. Here, our best fit model results are plotted along with our actual data results. Our results show a clear rotation curve running from SW to NE in the nucleus.

Fig. 6



EMISSION LINE GAS DISTRIBUTION

These images show the distribution of Hα-emitting gas on a large scale within the galaxy. Fig. 4a shows an ACS image using the F658N (Hα) filter, and Fig. 4b shows the same data, zoomed in, after continuum-subtraction. Fig. 4b also has the STIS slits overlaid at the correct position angles. The red box in Fig. 4a corresponds to the field of view (20x16") in Fig. 4b. Note that Fig. 4b is inverted- therefore, dark pixels show areas of bright Hα emission.

Fig. 4a

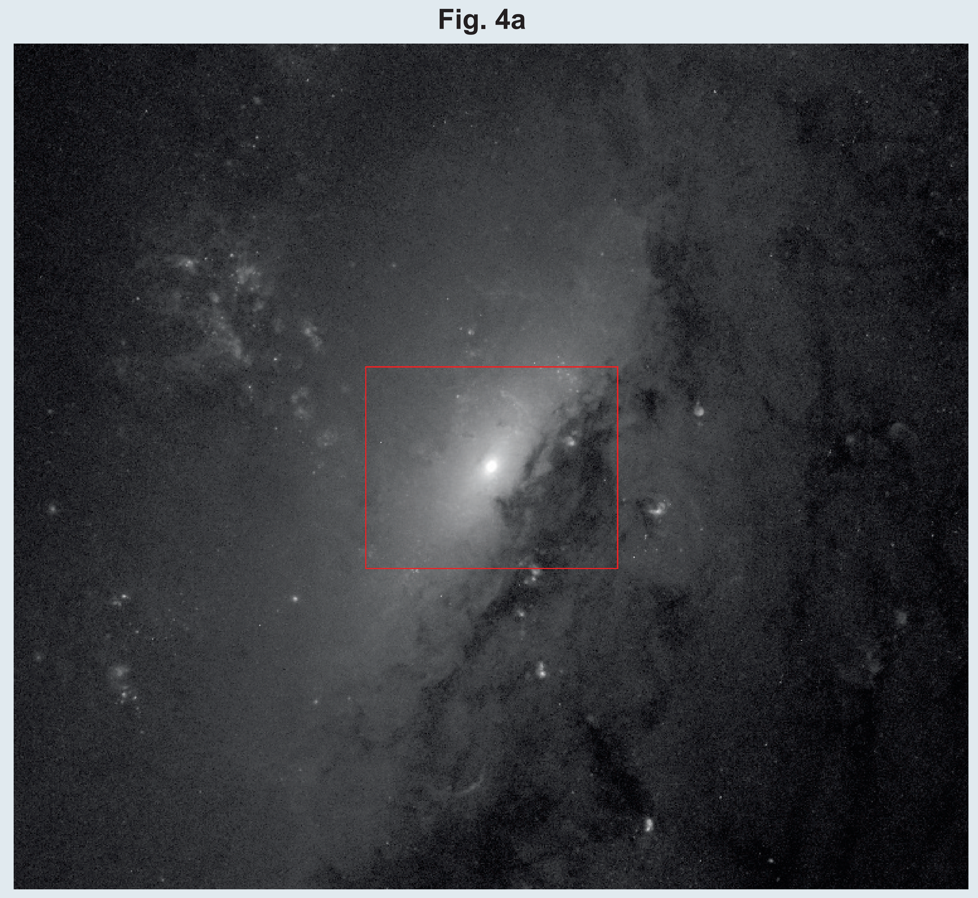
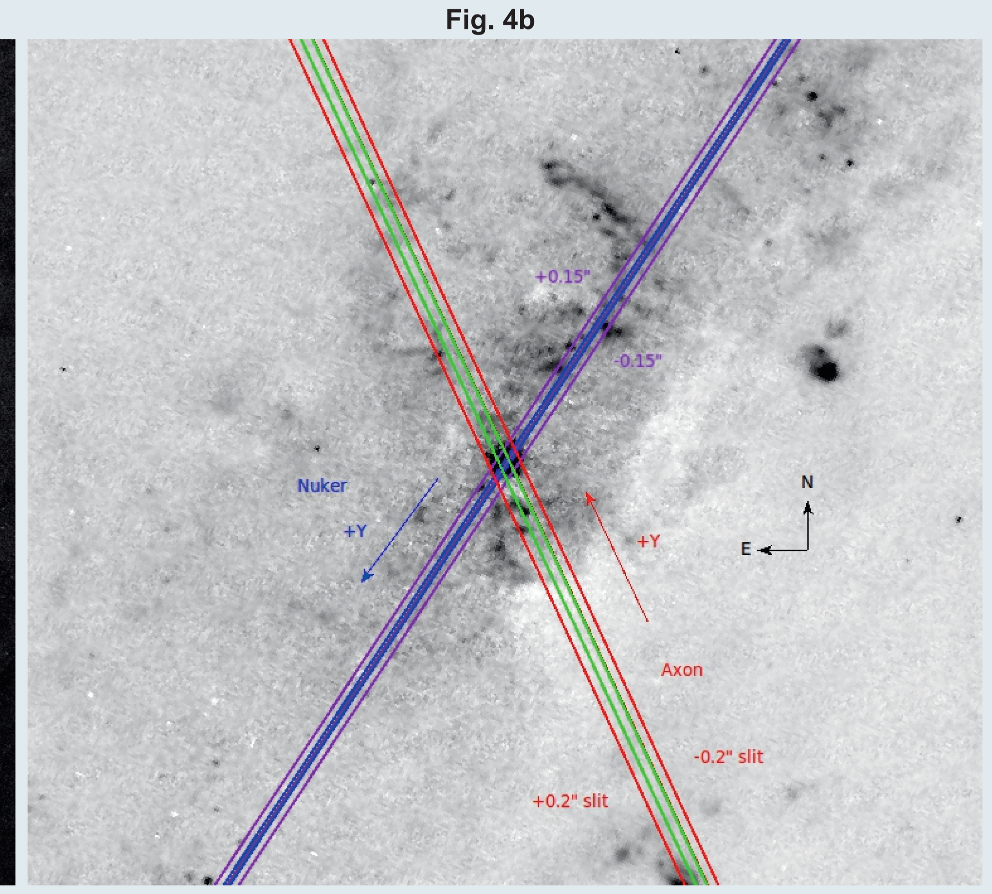


Fig. 4b



GAS DISK MODELING

Fig. 5 consists of several explanatory diagrams for our gas disk modeling.

- Fig. 5a is for the nuclear slit. CCW from top: Extracted 1D modeled spectra, the disk as seen through the slit, a 2D model spectrum in detector pixels, and a 2D model spectrum in subdivided pixels.
- Fig. 5b is as above, but for the -0.2" offset slit.
- Fig. 5c is a zoomed-in view of the nucleus. Running from the upper left to lower right, green contours show an extension of light that may correspond to the disk we are trying to model. The maser disk is also overlaid onto the image, both at actual size and scaled up by 50.
- Fig. 5d shows our three STIS 2D spectra. The red box indicates the limits of the model. Note how the apparent center of the galaxy shifts up and down for the offset slits, indicating that the aforementioned visible disk is real.

Fig. 5a

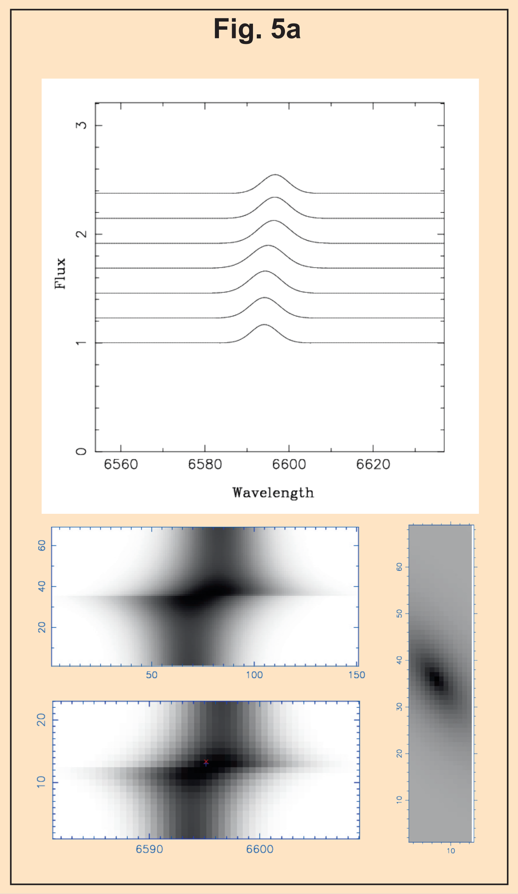


Fig. 5b

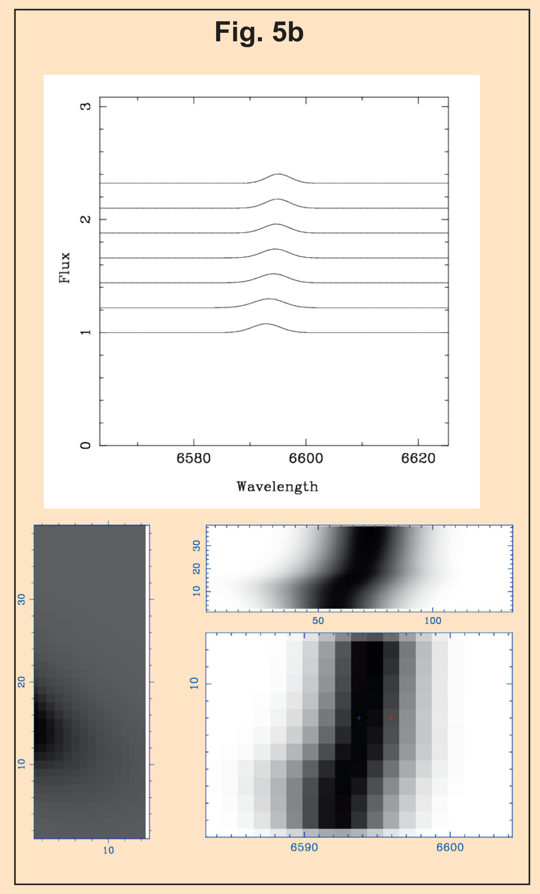


Fig. 5c

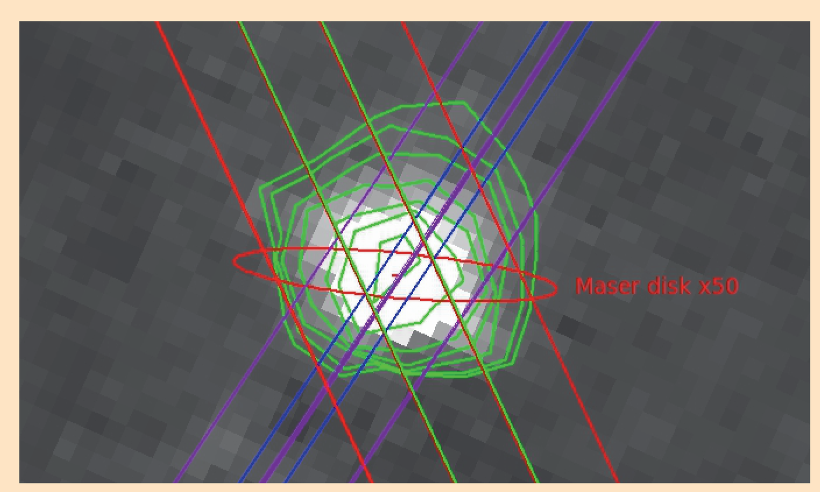
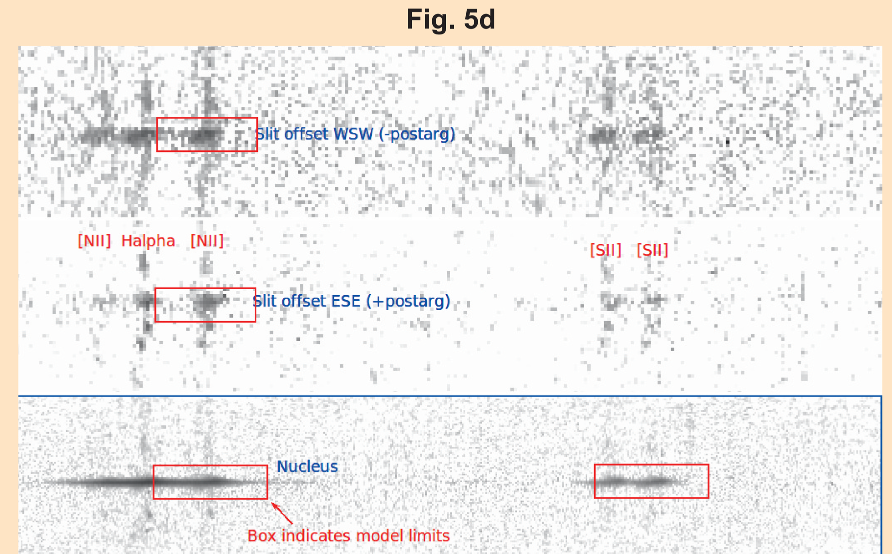


Fig. 5d



RESULTS

- Our rereduction and line-fitting of the Axon data gave very similar results to Pastorini et al (2007). See Figure 7.
- At small scales (0.8"), a disk appears to be visible in the ACS narrow-band images. It appears as an "extension" of the light from the nucleus on both sides at a PA of about 35˚ E of N. This disk morphology is also evident as a shift in the centroid of the galaxy light across our three slits. However, this visible light disk is rotated relative to the sub-parsec scale maser disk.
- Broad-line Hα emission is evident out to approximately 3.75 pc from the nucleus, with broad-line velocity dispersions of up to ~700 km/s.
- We modeled the emission line kinematics as resulting from a thin, inclined, disk of gas orbiting around the BH under the influence of gravity alone, and viewed through the STIS slit. (See best fit below.)
- Our mass estimate of $2x10^7 M_\odot$ is lower than the maser-based estimate of $3.9x10^7 M_\odot$ and the Siopis estimate of $3.3x10^7 M_\odot$, but the M/L is higher. The position angle of the best-fit modeled disk also differs from the visible nuclear disk by about 10 degrees.

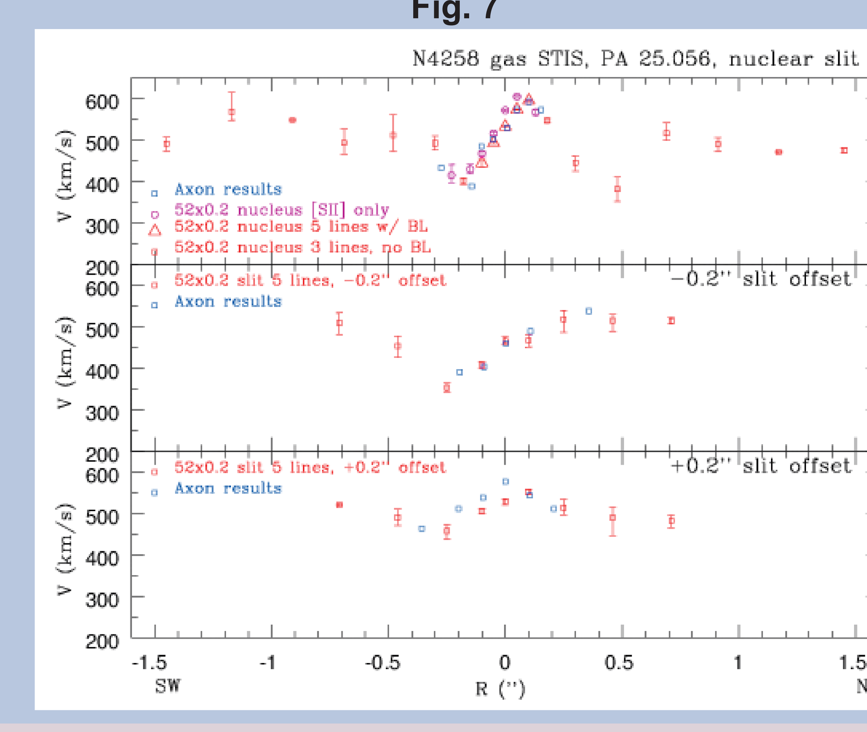
BEST FIT PARAMETERS	
Inclination	76˚
Slit rotation	-34˚
z-offset	0
y-offset	0.7
M/L_V	2.6
M_{BH}	$2x10^7 M_\odot$
Distance	7.6 Mpc

- Emission line distribution $I = I_0 e^{-r/rm}$
- Intrinsic dispersion distribution $\sigma = \sigma_0 + \sigma_1 e^{-r/rg}$
- Empirical star mass distribution (see Fig. 3)
- Added 10 km/s in quadrature to errors.
- X_v^2,v = 8.28, 25 dof. based on velocity only

FUTURE WORK

The data presented here is merely preliminary work. We plan on doing further gas disk modeling using the Nuker data as well as the Axon data. Despite being at a very different position angle, it can still be of some use. The ultimate goal is to compare the black hole mass obtained here to the well-defined mass obtained via maser measurements.

Fig. 7



REFERENCES

- Gebhardt, K. et al. 1996, AJ, 112, 105
- Herrnstein, J., et al. 2005, ApJ, 629, 719
- Humphreys, E., et al. 2013, ApJ, 775, 13
- Pastorini, G., et al. 2007, A&A, 469, 405
- Siopis, C., et al. 2009, ApJ, 693, 946

Acknowledgements

This work benefitted from the use of the NASA Extragalactic Database (NED).
This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.