Kinematics and black hole mass for the narrow-angle tailed radio galaxy NGC 4061

J. Pinkney (Ohio Northern University),
K. Gebhardt (UT Austin), and the Nuker Team.

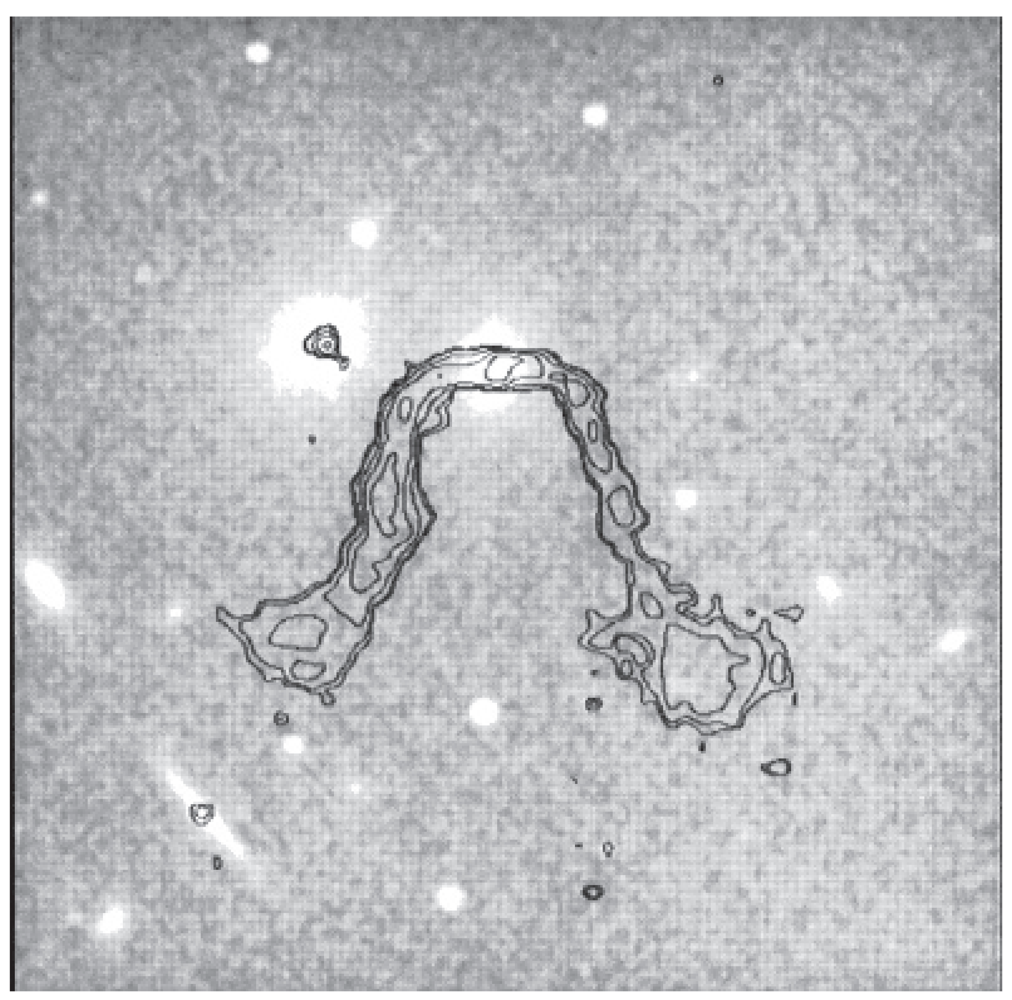
Abstract

In the quest to pin down the high-mass end of the $M_{BH} - \sigma$ correlation for galaxies, NGC 4061 may attract attention. It has the largest velocity dispersion 459 km s^{-1} in the Hypercat catalogue and, one would extrapolate, the most massive supermassive blackhole in the nearby universe. Here we present analysis of new spectroscopy and imaging from HST and the ground for NGC 4061. HST imaging reveals an organized dust disk with a radius of 2.5″. Our ground-based spectroscopy reveal central Hα emission from gas in rapid rotation. The velocity change is 270 km s^{-1} in 0.55″ (250 pc). This suggests a BH mass of about $2 \times 10^9 M_\odot$ (similar to M87 with $3.0 \times 10^9 M_\odot$). We also obtain stellar kinematics from the absorption lines of the calcium triplet (near IR) from the ground (MDM 2.4-m) and from STIS aboard HST. We fit losvd's and Gauss-Hermite moments using a new, direct-template-fitting code. We find the rotation to be strong in the stars as well. The central velocity dispersion is only about 290 km s^{-1}, so the black hole's sphere of influence is, in fact, not resolved.

Our measurements suggest that the large (459 km s^{-1}) dispersion was erroneous. Nevertheless, this galaxy is interesting in that it allows a comparison between the gas and stellar dynamical methods for determining BH mass. NGC 4061 is a promising target for future high-spatial-resolution spectrographs.

We acknowledge support for HST proposal 9106 from NASA through a grant from the STScI, which is operated by the AURA under NASA contract NAS 5-26555, and to an LTSA grant NAG5-8238 to D. Richstone.

FIG. 1. NGC 4061 is a Narrow-Angle Tailed radio galaxy residing in a poor cluster of galaxies. It is located near the X-ray centroid of the cluster.



IMAGING

FIG. 2. Our WFPC2 F555W image. LEFT: negative stretch. RIGHT: unsharp-masked, again negative, showing heavy dust as white and excess emission as dark.
Both F814W (I) and F555W (V) data were obtained. These were crucial for estimating the stellar mass profile for NGC 4061. The mass derives from the projected luminosity (after deconvolution), so the dust makes this case

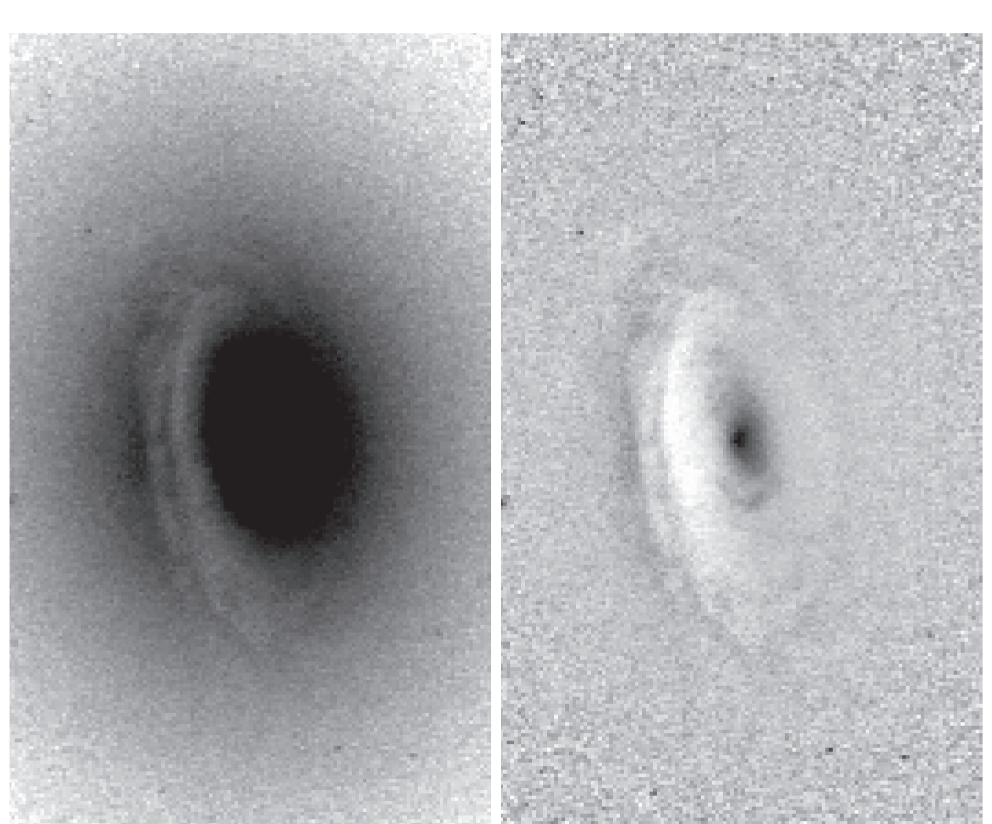
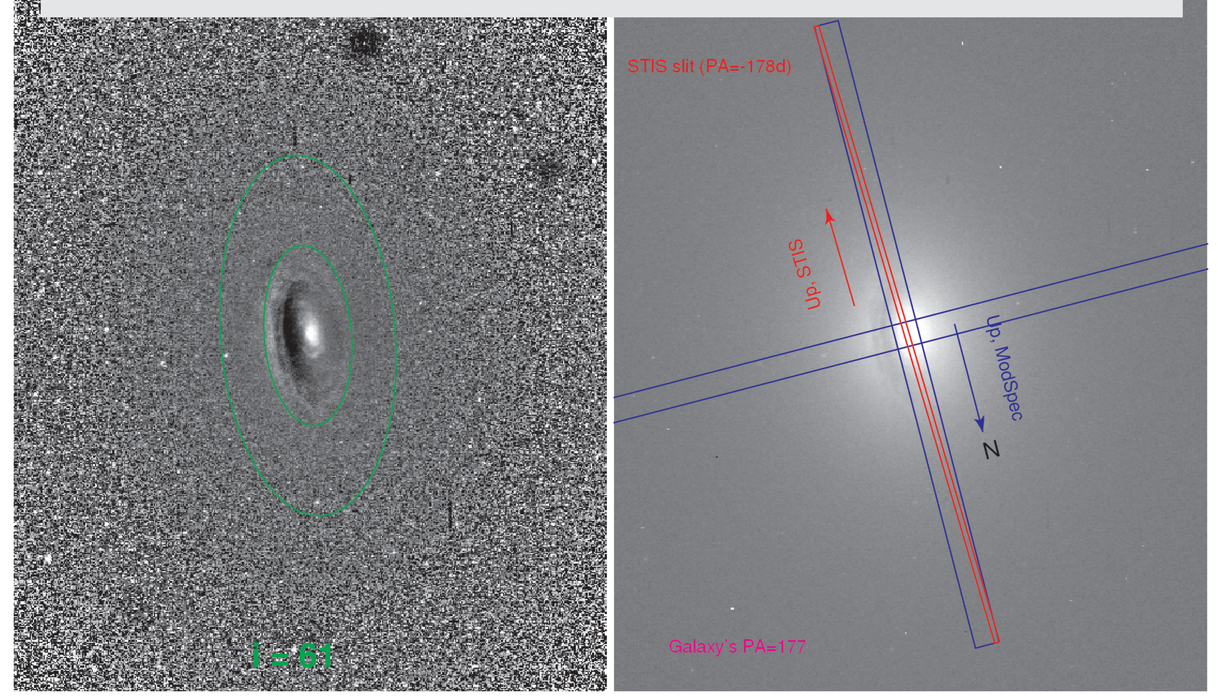


FIG. 2 WFPC2 imaging through the F555W and F814W (V,R) filters reveal an organized dust disk. This is typical for radio galaxies (Verdoes Kleijn et al. 2002). LEFT: Ellipse fits to the disk (using F555W) to find its inclination. RIGHT: Overlay of slits from STIS (magenta) and ModSpec (blue) observations. The STIS spectral range included Ca H&K (3933, 3969A). ModSpec (on the 2.4-m at MDM Observatory) was used for both the near-IR CaII absorption lines (8498 - 8662 A), and the Ha+NII emission lines.



SPECTROSCOPY

FIG. 4. Sample spectra from STIS (Space Telescope Imaging Spectrograph) taken using the G430L setup.

TOP: NGC 4061. Extracted from the central 0.75 arcseconds (15 rows) of the combined STIS data. This is a core galaxy with a low central surface brightness, but the low spectral resolution (2.75 A/pix) improves the S/N.

BOTTOM. HD141680. A G8 III star used as a template for determine the broadening function, and thus stellar kinematics, in NGC 4061. Both non-parametric and parametric fits (e.g., Gauss-Hermite polynomials) are used to find the best line-of-sight velocity distributions (LOSVD) at each position along the slit.

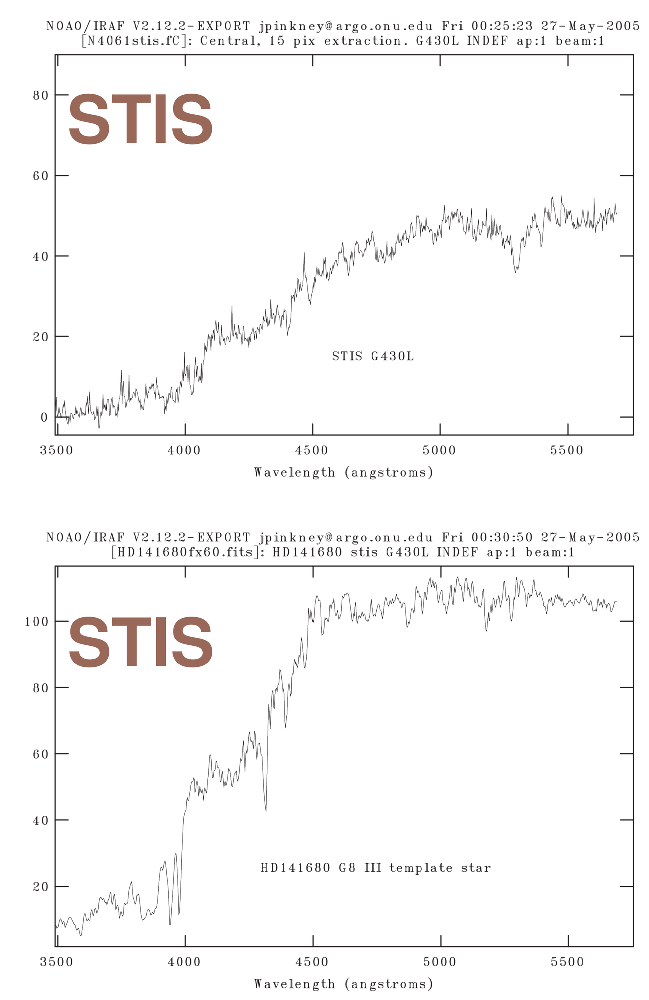


FIG. 5. ModSpec spectra of Ha+NII emission. The untouched, reduced data is shown in panel (A), while panels (B),(C), and (D) offer three ways to show the emission above the continuum.
These simple lines are the main focus of gas kinematics analysis -- we do not have any higher resolution Ha spectra.

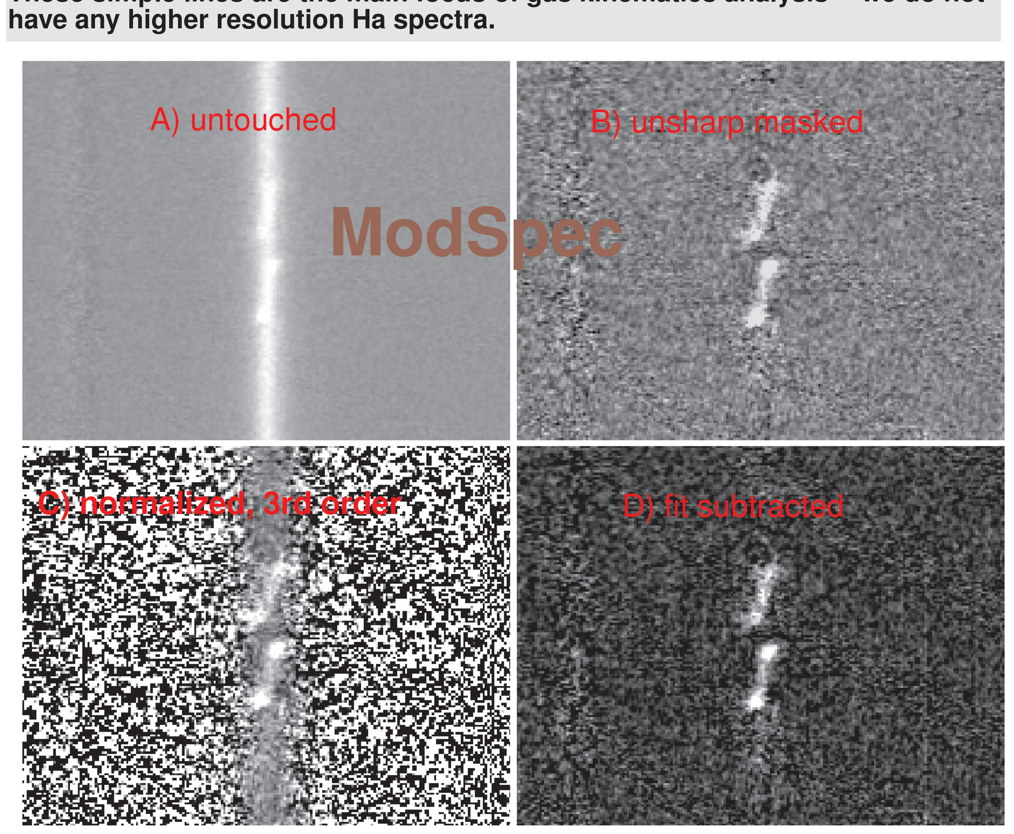
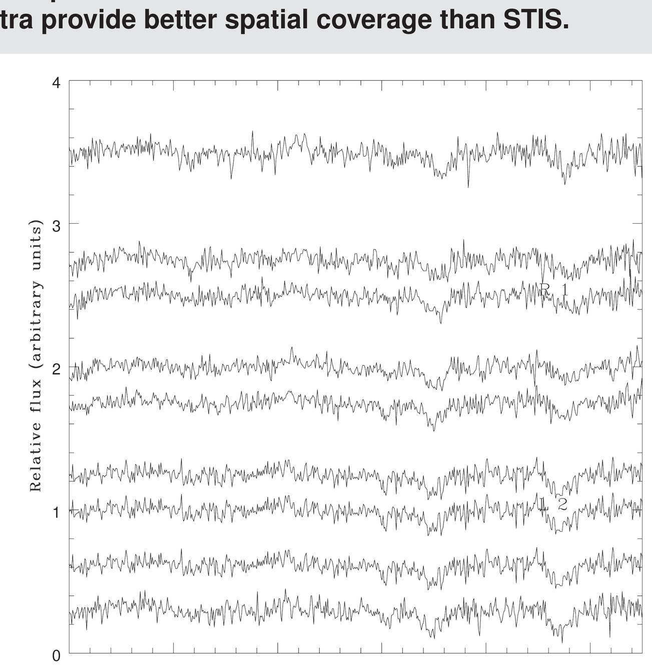


FIG. 6. ModSpec infrared CaII data. The calcium triplet (8498, 8542, and 8662 A)are the absorption lines most suitable for stellar kinematics. The ground-based spectra provide better spatial coverage than STIS.



LINE FITTING

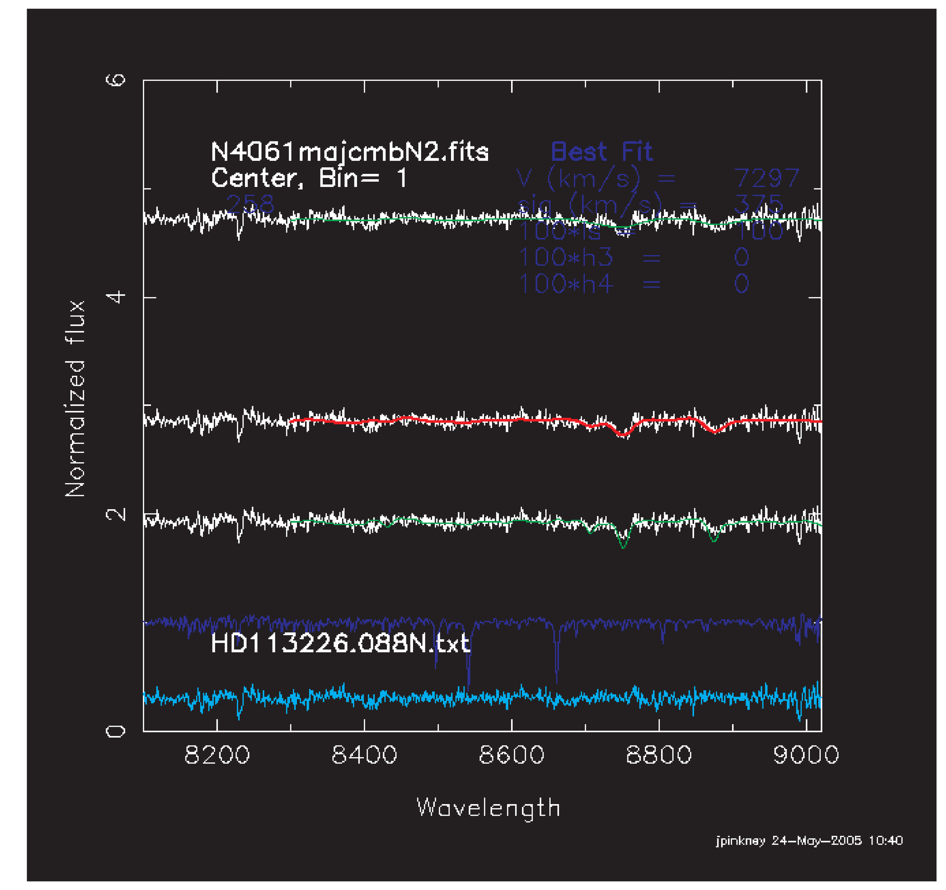


FIG. 7. Sample output from our line-fitting program.
This uses direct fitting (Barth et al. 2002) as opposed to FCQ or MPL to determine 5 parameters describing the lines position and shape. These "losvds" contain kinematic information. Both plots show best-fit parameters (blue, right), chi2 (blue left), names of the input galaxy and template star spectra (white top, bottom), bin id (white, right), the galaxy spectrum (white, 3 positions), template spectrum (blue), best fit broadened template (red), fits using a dispersion 2x (green, top) and 1/2x (green, bottom) the best fit value, and the residual of the best fit (teal, bottom)
ABOVE. Applied to ModSpec CaT (absorption) data. Here we can address the question "How did White et al. (1983) measure a velocity dispersion of 477 km/s for NGC 4061?" Most of our best estimates are in the 250-300 km/s range. However, we can maximize dispersion by binning data from both sides of the galaxy center and by using a large linestrength (LS) parameter. This plot shows sigma=375 km/s. We could not reach 477 km/s. The implication is that the sphere of influence of the BH is not resolved, making BH mass difficult to determine.
BELOW. Applied to ModSpec Halpha (emission) data. This plot was chosen to show how large H3 and H4 parameters can create double-peaked losvd's. These can provide better fits for complex lines, but a physical interpretation is difficult. Our program allows absorption subtraction prior to emission line

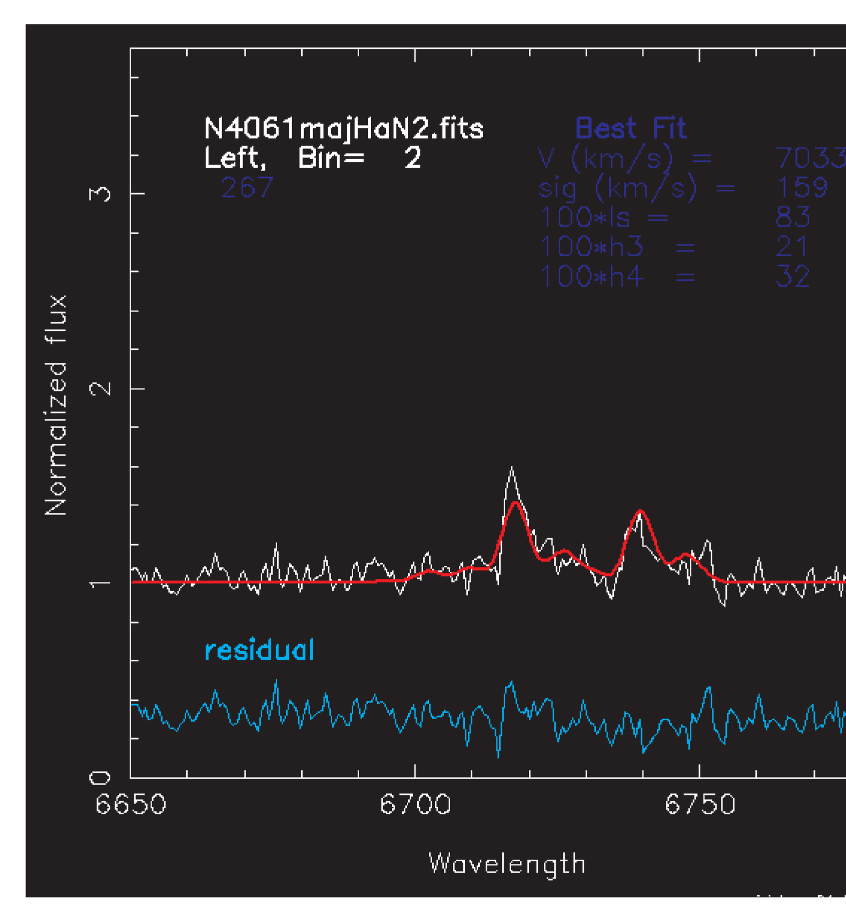


FIG. 8. (BELOW) Kinematics of stars (circles) and gas (X's) from ground-based spectroscopy. The end points have large uncertainties due to low S/N. The dispersion profiles are especially sensitive to the number of parameters

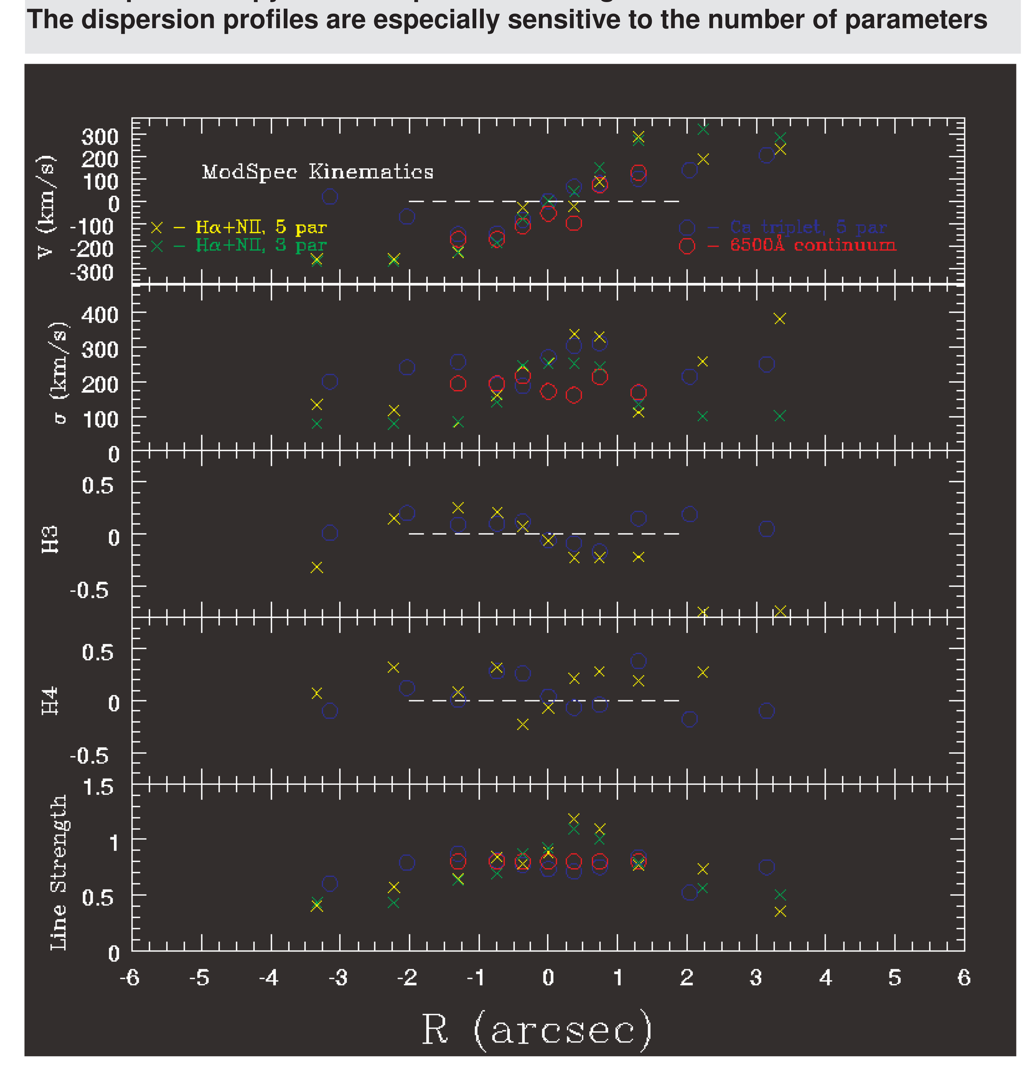
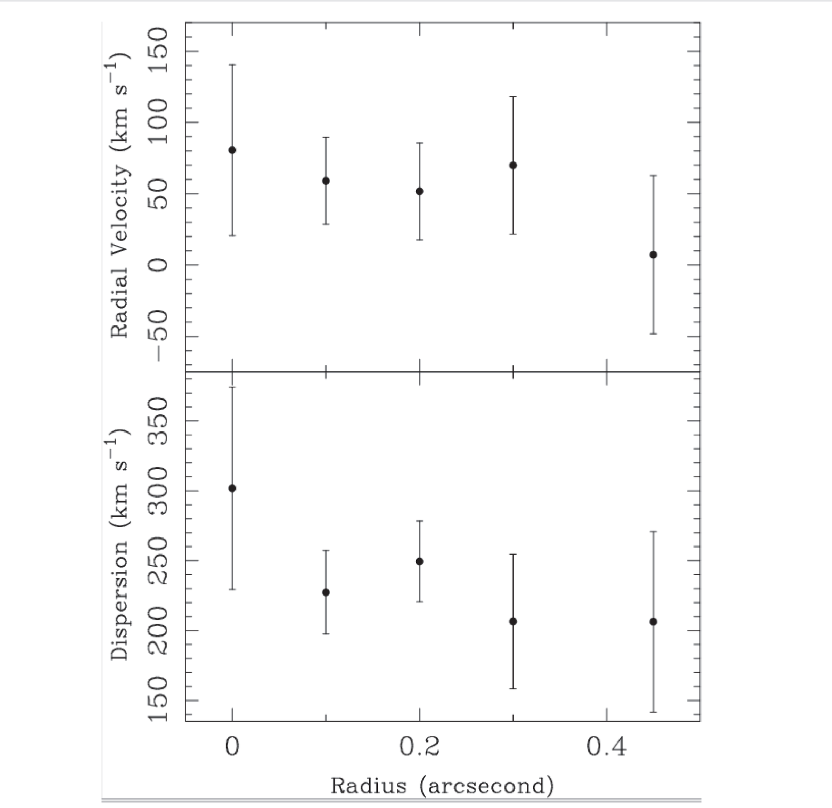
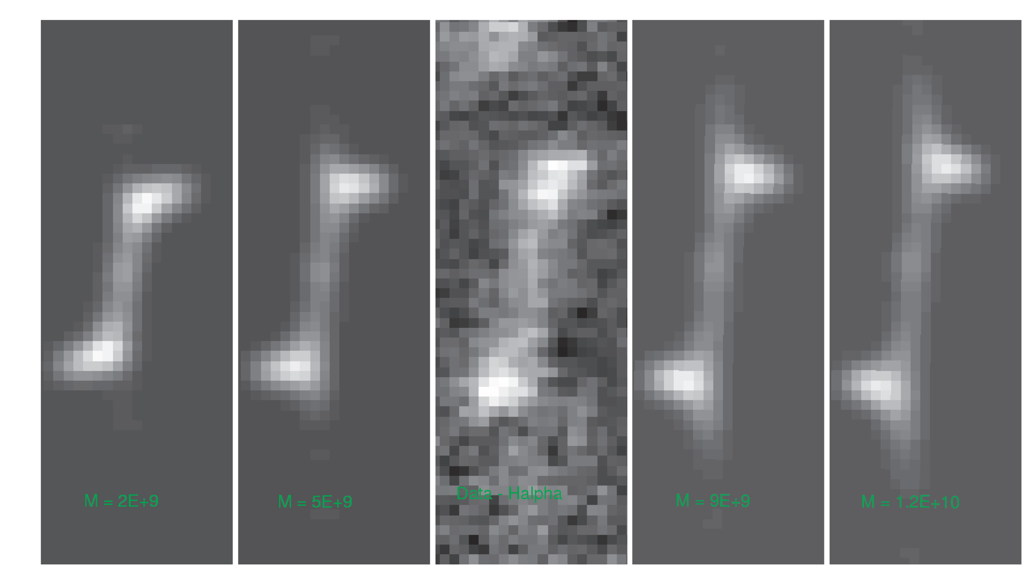


FIG. 9. (BELOW) Kinematics derived by non-parametric losvd-fitting of the G430L major axis data. Top: radial velocity. Bottom: velocity dispersion. The two sides of the galaxy are symmetrized to produce these plots.



MASS MODELING

FIG. 10. Modeling the light distribution on a 2D spectrum. The real, ModSpec data is in the center, flanked by models. The model parameters (see table below) are identical except for the BH mass. There are actually two prominent emission lines (see FIG. 6), but we just show the bottom (H alpha) line. The vertical separation between the bright spots is a good measure of the BH mass.



Mass Modeling

NGC 4061 is one of a handful of galaxies to which both the stellar and gas kinematics techniques can be applied for determining the mass of the central black hole. We have preliminary results from several methods.

1. Stellar kinematics. So far, we have produced spherical isotropic models to match the imaging and STIS Ca H&K spectroscopy. This gives $\boldsymbol{M_{BH} = 1.0 \times 10^9 M_\odot}$.
2. Gas kinematics: simple, two-point calculation. Here we choose two positions, $r = \pm 1.3''$, fit Gaussians to the 2 emission lines (both simultaneously), and obtained $V_{obs}(r)$ for $r = 1.3''$. Then the circular velocity, $V_c = \frac{V_{obs}}{sin i}$ is used in $M(r) = (233.5 M_\odot) V_c^2 r$. Finally, we subtract the stellar mass enclosed within r determined from photometry. We assume that the gas is all co-planar and rotating in circular orbits. This gives $\boldsymbol{M_{BH} = 2.2^{+2}_{-1} \times 10^9 M_\odot}$.
3. Gas kinematics: 2-dimensional spectrum comparison. Here we have generated 2D spectra matching the ModSpec Hα data. They include details such as the slit width effects, seeing, and slit orientation (as in Maciejewski & Binney 2000). The model and data can then be compared side by side to find the best match. FIG. 10 suggests that $\boldsymbol{M_{bh} = 3 - 9 \times 10^9 M_\odot}$.

	Parameters used	Value
i	galaxy inclination	61°
D	galaxy distance	100. Mpc[a]
sw	Modspec slit width	0.8″
sclas	Modspec scale along slit	0.371″ pix^{-1}
sa	Modspec slit offset from disk maj axis	5°
disp	Modspec reciprocol dispersion	0.62 Åpix^{-1}
psf	Modspec seeing FWHM	1.1″

[a] $H_0 = 72 km s^{-1} Mpc^{-1}$

Results and conclusions

1. The BH in NGC 4061 has a mass in the $1 - 9 \times 10^9 M_\odot$ range.
2. The gas kinematics is giving higher BH masses than the stellar techniques. However, they are still in rough agreement at this stage. The stellar models do not yet include the ground-based calcium triplet data at 3 position angles, and they can be more sophisticated than an isotropic sphere.
3. The $M_{bh} - \sigma$ relation (in Tremaine et al. 2002) predicts $M_{bh} = 6.9 \times 10^8 M_\odot$ for the stellar velocity dispersion we measure for NGC 4061 ($\sigma \sim 300$ km s^{-1}). Thus, the NGC 4061 data point lies above the ridgeline of the relation.
4. NGC 4061 may become the highest measured BH mass to date! The current record holders are M87 ($3.0 \times 10^9 M_\odot$), IC1459 ($2.5 \times 10^9 M_\odot$), and NGC 4649 ($2.0 \times 10^9 M_\odot$).

A product of Ohio Northern University