STIS Spectroscopy of the Central 10 pc of M81: Evidence for a Massive Black Hole

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ABSTRACT

Spectroscopic observations of the central 10pc of M81 were obtained with STIS aboard the Hubble Space Telescope during Cycle 7. Measurements of the Hα+[NII] blend reveal a velocity field indicative of a rotating disk of gas. The two dimensional velocity field has been modeled as a thin disk rotating in a spherical gravitational potential. Minimizing the difference between the model and the observations allows useful constraints to be placed on the mass of the black hole in this mini Seyfert 1 galaxy. The data suggest that the mass of the nuclear black hole in M81 is \((7.0^{+2}_{-1}) \times 10^7 M_\odot\) and that the normal to the disk is inclined at an angle of 14 ± 2 degrees to the line of sight.

Subject headings: galaxies: individual (M81, NGC 3031), galaxies: Seyfert

1. Introduction

One way to elucidate the evidence for black holes in the nuclei of galaxies is to measure the gas kinematics and demonstrate rotational velocities in excess of that expected from stars. A two dimensional kinematic map is required to correctly identify the kinematic line of nodes which, for practical reasons, may not necessarily lie along the direction chosen for the slit. The map may then be used, with appropriate modeling, to constrain both the mass of the black hole and the inclination of the gas disk from which the rotational velocities are derived.

Ground based spectroscopic measurements aimed at mapping the two dimensional velocity field in the central few parsecs of nearby galaxy nuclei are severely compromised by limited angular resolution. The Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (HST) is therefore a very important instrument as it provides the only
opportunity to reliably map the two dimensional gravitational potential with an angular resouion of 0′.1. M81, at a distance of 3.6 Mpc (Freedman et al. 2001), is the nearest example of an AGN with a directly observable nucleus. Because HST’s exquisite angular resolution is fixed, the minimum detectable black hole mass (M_{BH}), and the minimum detectable radius of influence of the M_{BH}, both scale with distance. Consequently, M81, with a minimum detectable M_{BH} \sim 10^6 M_\odot, provides one of the best opportunities for pinning down the lower end of the M_{BH} mass function in luminous galaxies beyond the Local Group.

Existing observations reinforce a growing body of evidence that M81 hosts a bonafide AGN, albeit a low luminosity one. The evidence includes broad optical and UV emission lines (Peimbert & Peimbert 1981), a featureless UV continuum (Ho, Fillipenko & Sargent 1996), a compact optical/UV continuum source embedded in an extended narrow line region (Devereux, Ford & Jacoby 1997), and an ultra compact radio source that is associated with a radio jet (Bietenholz, Bartel, & Rupen 2000). The nucleus also varies with time at radio (Ho et al. 1999), optical (Bower et al. 1996) and X-ray wavelengths (Iyomoto & Kazuo 2001).

The broader context for the current investigation is the recent discovery that black hole mass and bulge velocity dispersion are correlated in normal galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000a). Such a relationship suggests that the growth of the central black hole may be related to the evolution of the host galaxy. The correlation also holds for luminous AGNs (Ferrarese et al. 2001) if one adopts the black hole masses yielded by reverberation mapping. In the context of black hole demography, M81 provides an opportunity to quantify the low end of the black hole mass function as nature has conveniently provided an ionized gas disk in the nucleus, the kinematics of which are the subject of this paper.
The observations are described in section 2 followed by a brief discussion of the data reduction procedure in section 3. An overview of the principal results and analytical methodology is provided in section 4. The discussion and conclusions are presented in sections 5 and 6 respectively.

2. Observations

The STIS observations of M81 were obtained during Cycle 7 on July 14, 1999. M81 was centered on the 1024 x 1024 pixel STIS CCD, using an onboard target acquisition peakup, in the F28X50LP optical longpass filter. The spectroscopic observations were obtained with the 0.1 arc second slit and the G750M grating centered at 6581 Å dispersing the 6295 - 6867 Å light over 1024 pixels yielding an average spectral dispersion of 0.56 Å/pixel. The wavelength range includes the bright H$\alpha$+[NII] emission line blend bracketed by [OI] 6364 on the shortward side and [SII] 6717, 6730 on the longward side. Spectra were obtained at seven contiguous positions parallel to each other and oriented along the major axis of the ionized gas disk (Devereux, Ford & Jacoby 1997). The spectra were CR-SPLIT for a total integration time of approximately 1000 seconds at each slit position. The 52 arc second long slit was imaged onto the CCD yielding an angular scale, perpendicular to the dispersion direction, of 0.05 arc seconds per pixel.

3. The Data

The spectra were calibrated using CALSTIS which is the standard pipeline processing procedure for STIS data. CALSTIS flat-fields and combines CR-SPLIT exposures into a single wavelength and flux calibrated cosmic ray rejected image. The STSDAS task X1D was then used to extract one dimensional spectra from the calibrated images. Each
image was oversampled in the cross dispersion direction by extracting spectra, two pixels wide, every 0.05 arc seconds. Only the highest signal to noise data were included in the following analysis. The fainter emission in the outer two slit positions was excluded as were measurements made beyond 0.45 arc seconds from the nucleus in each extracted spectrum. The resulting dataset yielded a 5 x 19 grid of high quality spectra centered on the bright nucleus of M81.

The spectrum obtained at the position of the nucleus of M81 is presented in Figure 1 and shows the bright [NII] emission lines sitting on a very broad Hα emission line which is itself flanked by the [OI] and [SII] emission lines. The following semi-interactive procedure was employed in using the STSDAS contributed task SPECFIT to model the narrow lines in the STIS spectra. First, a power law was fit to the line free continuum between 6400 - 6425 Å on the blue side, and between 6690 - 6700 Å on the red side, of the Hα+[NII] blend. Next, the brightest of the [NII] lines was fit between 6570 and 6600 Å, holding the continuum level fixed. Fitting the fainter [NII] line directly is precluded by the fact that it is hidden behind the broad Hα blend. However, the intensity (and linewidth) relative to the brighter [NII] line is determined by atomic physics to be in the ratio 1:3 since both [NII] lines originate from the same upper level. The narrow component of the Hα line is fit between 6555 and 6570 Å, whilst holding the fit to the continuum level and the [NII] lines fixed. The broad Hα line was not fit owing to the fact that it is not a gaussian, but the flux in the broad line can be determined quite easily by subtracting the fitted narrow line components as illustrated in Figure 1. The remaining [OI] line and the two [SII] lines could be fit quite easily as they are well displaced from the Hα+[NII] blend. The resulting model line parameters are summarized in Table 1 for the nuclear spectrum, and the wavelengths of the brightest [NII] line, from which the velocity field is derived, is presented in Table 2 for all the extracted spectra.
4. The Results

4.1. The Observed Two Dimensional Velocity Field in M81

The wavelength of the vacuum wavelength $\lambda_o = 6585.28$ [NII] line could be measured with confidence ($\pm 0.1 \, \text{Å}$) over the entire $5 \times 19$ grid of extracted spectra and the results are listed in Table 2. The wavelength of the $6585$ [NII] line was exclusively used to quantify the observed two dimensional velocity field, $\bar{V}(r_{\text{sky}}, \phi)_{\text{obs}}$, by converting the Doppler shifts $\Delta \lambda$ into a radial velocities using

$$\bar{V}(r_{\text{sky}}, \phi)_{\text{obs}}/c = \Delta \lambda/\lambda_o$$

(1)

where $r_{\text{sky}}$ and $\phi$ are the radius vector and position angle on the plane of the sky, and $c$ is the speed of light. The oversampled measurements in the cross dispersion direction were block averaged to yield a uniform spatial grid and the resulting two dimensional velocity field measured for the central $0.4 \times 0.9$ arc sec region of M81 is shown in Figure 2. The long axis of the slit runs vertically in this diagram. It is gratifying that Figure 2 reveals the signature of rotation. The peak to peak velocity amplitude is 110 km/s and is symmetric about the nucleus for a systemic velocity of $-46$ km/s which is in good agreement with previous measurements indicating a blueshift for M81 (Ford, Rubin & Roberts (1971), Goad (1974)). Figure 2 indicates that the kinematic line of nodes lies along a position angle of 146 degrees which is close to the value of 150 degrees typically adopted for the position angle of the major axis for M81 (eg. Goad (1976)).
4.2. The Model Two Dimensional Velocity Field in M81

We model the gravitational field strength in the central 10 pc of M81 as the sum of a spherically symmetric distribution of stars and a central point mass representing the black hole, $M_{BH}$. Regretably, the starlight emanating from the nucleus of M81 can not be measured directly as it is overwhelmed by the bright AGN. Thus, the stellar mass distribution is inferred by extrapolating the larger scale stellar surface brightness profile and adopting a constant mass to light ratio for the stars.

Prior ground based (Devereux, Jacoby & Ciardullo 1995) and HST V band imagery (Devereux, Ford & Jacoby 1997) are combined to define the stellar surface brightness profile for the central 30 arc seconds of M81 as shown in Figure 3. The figure shows good agreement in the region of overlap between the ground based and space based data.

An important question concerns the impact of the bright AGN on the surface brightness profile. A star in the F547 continuum image was used to represent the WFPC2 point spread function which was superimposed on the nucleus of M81, scaled, and then subtracted. Bower et al. (1996) suggest that the AGN may contribute as much as $\sim 70\%$ of the total V band light in the central 0.2 arc second region based on the absence of certain stellar absorption lines in a Faint Object Spectrograph spectrum. An alternative estimate of a 50% AGN contribution is provided by our analysis where the scaling is chosen so that the residual, following the subtraction, does not fall below the extrapolation of an $r^{1/4}$ law fitted to the bulge light, illustrated as a solid line in Figure 3. The diagram suggests that the AGN has little consequence on the radial surface brightness profile for radii greater than 0.4 arc second. Thus, the starlight can be traced reliably to within 7 pc of the AGN. There is no data for $r \leq 0.1$ arc sec, as this is the size of a single WFPC2 pixel. At larger radii, beyond 16 arc seconds, the surface brightness profile appears to flatten out, perhaps indicating the onset of an exponential disk component. For the purposes of parameterizing
the inner bulge of M81, a least squares fit to the photometry between $1.0'' \leq r \leq 16''$ yielded the following $r^{1/4}$ law,

$$\mu = (2.63 \pm 0.01)r^{1/4} + (12.43 \pm 0.02)$$

(2)

where $\mu$ is in magnitudes/(arc sec)$^2$ and $r$ is in arc seconds.

Thus, the visual surface brightness profile yielded an extrapolated central surface brightness $\mu_o = 12.43$ mag/arc sec$^2$, an effective radius $r_e = 99.5''$, and a bulge luminosity, $L_{\text{bulge}} = 5.44 \times 10^9$ L$_\odot$, based on a distance to M81 of 3.63 Mpc (Freedman et al. 2001).

Scaling laws appropriate for spherical bulges that allow one to correct the observed luminosity for the line of sight contribution of foreground and background bulge stars are derived by Young (1976). The correction is substantial. In the central 10 pc of M81, the deprojected luminosity is $\lesssim 1/20$ of that inferred from the integrated light.

$M(R)$, the stellar mass interior to a radius $R$ within the galaxy, is calculated using

$$M(R) = M^*(s) \left[ M/L \right]_{V} L_{\text{bulge}} M_\odot$$

(3)

where $M^*(s)$ is the reduced mass and $s = R/r_e = \alpha = r_{\text{sky}}/r_e$ (for a sphere), in the nomenclature of Young (1976).

The $[M/L]_V$ for the stars in the central region of M81 has been estimated two different ways. The first is statistical, based on an empirical mass-luminosity relationship determined in the near infrared for a sample of ellipticals, lenticulars and early type spiral bulges (Devereux, Becklin & Scoville 1987). Color correcting the average $[M/L]_H$ to the V band using $V - H = 3.2$ measured for M81 by Aaronson (1977), yields an average $[M/L]_V = 4.5$ for a bulge with the color of M81. A comparison can be made with the bulge of M31 for
which \([M/L]_B = 6\) (Simien, Pellet, Monnet 1979) and \([M/L]_I = 2.5\) (Bacon et al. 1994) which yield \([M/L]_V = 3.6\) and 4.0 for the bulge of M31, respectively, when color corrected to the V band. In the following, a median value of \([M/L]_V = 4.0\), is adopted for the bulge of M81. The resulting run of \(M(R)\) with \(R\), calculated using equation 3, is presented in Table 1.

The circular velocities, \(V(R)\), expected for a thin disk spinning under the influence of \(M(R)\), are listed in Table 1 and calculated using

\[
V(R) = 6.56 \times 10^{-2} \sqrt{(M(R)/R)}
\]

(4)

where \(V(R)\) is in km/s, \(R\) is in parsecs, and \(M(R)\) is in solar units.

The disk is not necessarily viewed edge-on so the sky coordinates, \(r_{sky}\), must be projected to face-on galaxy coordinates, \(R\), in order to utilize \(V(R)\) successfully. If the normal to the disk is inclined to the line of sight by an angle \(i\), so that an edge-on disk would have \(i = 90^\circ\), the following transformations apply

\[
R^2 = r_{sky}^2 \left[ \cos^2 \phi + \sin^2 \phi \cos^2 i \right]
\]

(5)

and

\[
\tan \theta = \tan \phi / \cos i
\]

(6)

where \(\theta\) is the position angle of the radius vector \(R\) in the plane of the disk.

The stellar component alone is unable to satisfactorily account for the observed velocity amplitude in M81 because the observed velocity peaks closer to the nucleus than the stellar
mass distribution permits, so, $M(R)$ is amended with a point mass at the origin, $M_{BH}$, such that the circular velocity becomes

$$V(R) = 6.56 \times 10^{-2} \sqrt{(M(R) + M_{BH})/R}$$  \hspace{1cm} (7)

The observed velocity field measured by STIS depends on both $R$ and $\theta$ because the radial component of the velocity vector, directed along the line of sight, is given by

$$V(R, \theta) = V(R) \cos \theta \sin i$$  \hspace{1cm} (8)

A further transformation is necessary if the spectrograph slit is not aligned with the kinematic line of nodes as is the case for the STIS observations of M81 reported here. If $KA$ is the angle of the kinematic line of nodes measured clockwise from the $y$-axis of the sky coordinate system, then

$$\phi = \arctan(x_{sky}/y_{sky}) - KA$$  \hspace{1cm} (9)

When planning the M81 observations, we assumed that the gas disk imaged by Devereux, Ford & Jacoby (1997) was intrinsically circular in shape, and that the ellipticity indicated the inclination. However, the kinematic line of nodes for the nuclear $\sim 10$ pc gas disk is offset from the larger $\sim 100$ pc disk major axis by 34 degrees, suggesting that the larger scale disk is warped. A similar phenomenon was found in NGC 4261 and NGC 6251. In NGC 4261 (Ferrarese, Ford & Jaffe (1996)) the difference between the kinematic line of nodes in the inner disk and the major axis of the arc-second scale dust disk is 36$^\circ$. In NGC 6251 (Ferrarese & Ford (1998)) the kinematic line of nodes of the inner disk is rotated $\sim 55^\circ$ with respect to the major axis of the larger dust disk, and the inclination changes from
∼ 76° in the dust disk to ∼ 35° in the inner ionized disk. Evidently, warps are common in the small disks orbiting massive black holes.

For the STIS observations of M81, since the slit was aligned along the major axis of the ionized gas disk, rather than the major axis of the host galaxy, a value $K_A = 34$ degrees is adopted in equation 9, corresponding to an astronomical position angle (degrees east of north) of 146 degrees. Thus, the kinematic line of nodes for the nuclear gas disk in M81 is very closely aligned to the major axis of the host galaxy after all.

4.3. The Intensity Weighted Velocity Image

The observed velocity map produced from the STIS observations represents an intensity weighted average convolved with the resolution of the instrument. Thus, the model velocity field, described in the previous section, must also be appropriately weighted and convolved before a useful comparison can be made with the observations.

Mathematically,

$$
\bar{V}(r_{sky}, \phi)_{\text{model}} = I(r_{sky}, \phi) \times V(r_{sky}, \phi) \otimes lsf(r_{sky}, \phi) \div \{ I(r_{sky}, \phi) \otimes lsf(r_{sky}, \phi) \} \quad (10)
$$

where the intensity weighted velocity field, $\bar{V}(r_{sky}, \phi)$, is equal to the product of the light intensity, $I(r_{sky}, \phi)$, and the model velocity field, $V(r_{sky}, \phi)$, convolved with the line spread function, $lsf(r_{sky}, \phi)$, and normalized by the light intensity convolved with the line spread function.

A suitable representation of $I(r_{sky}, \phi)$ is provided by the WFPC2 continuum subtracted Hα emission line image of the ionized gas disk in M81 described by Devereux, Ford & Jacoby (1997). The Hα image was deconvolved to obtain the best possible representation
of the intrinsic light distribution. The brightest star in the ancillary F547 continuum image was used as a point spread function and a Lucy deconvolution algorithm yielded a satisfactory result with the deconvolved H\(\alpha\) image of the nucleus showing a FWHM of 0.25\(\arcsec\), down from 0.39\(\arcsec\) in the original image. A segment of the deconvolved H\(\alpha\) emission line image corresponding to the area mapped with STIS is presented in Figure 4.

The line spread function, \(lsf(r_{sky}, \phi)\), is the point spread function integrated across the slit (ie. the dispersion direction), at each position along the slit (ie. the cross dispersion direction). As such, the line spread function quantifies the response of STIS to a point emission line source. The H\(\alpha\) broad line region in M81 is unresolved as evidenced by the fact that the flux measured in our 0.1 \(\arcsec\) slit at the location of the nucleus (see Figure 1); \((9.56 \pm 0.02) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\) is identical to that measured in a larger 0.21 \(\arcsec\) square aperture with the Faint Object Spectrograph by Bower et al. (1996). Thus, the broad component of the H\(\alpha\) emission line is a suitable spectral line point source with which to measure the STIS line spread function.

The line spread function, \(lsf(r_{sky}, \phi)\), represented by the intensity image of the broad component of the H\(\alpha\) emission line, is shown in Figure 5. The line spread function is essentially symmetrical with a FWHM \(\sim 0.1\ arcsec\) in the dispersion direction consistent with the value quoted in the STIS Instrument Handbook. The image presented in Figure 5 is therefore adopted as the best representation of the line spread function for the instrumental configuration prevailing during the STIS observations of M81.

4.4. Comparison with the Observations

A grid of velocity models were computed for a variety of disk inclinations, \(5^\circ \leq i \leq 50^\circ\), and black hole masses, \(10^6 M_\odot \leq M_{BH} \leq 5 \times 10^8 M_\odot\). Each model was transformed into an
intensity weighted velocity map according to equation 10, and formally compared with the observations by computing the value of $\chi^2$ where

$$\chi^2 = \sum_{\text{pixels}} (\bar{V}(r_{sky}, \phi)_{\text{model}} - \bar{V}(r_{sky}, \phi)_{\text{obs}})^2 / \sigma^2$$ (11)

The error map, $\sigma$, was represented by a uniform array of numbers set equal to 5 km/s, the typical measurement uncertainty. However, the actual $\sigma$, measured by differencing the data and the model velocity maps, far exceeded that anticipated for measurement uncertainties alone. The discrepancy is the evidence, in fact, for non-circular motions with a standard deviation of the order of 15 to 20 km/s in the central 10pc of M81. An image depicting the spatial distribution of these non-circular velocities is shown in Figure 6. The origin of the non-circular velocities is unknown and modeling them is beyond the scope of this paper. However, we note in passing that the non-circular velocities are unlikely to be due to a bi-directional outflow, or inflow, as the magnitude of the deviant velocities is simply too small. Nevertheless, for the purposes of incorporating this additional uncertainty in the calculation of $\chi^2$, the value of $\sigma^2$ was expressed as the sum of two terms; the velocity measurement uncertainty $\sigma^2_v$ and the non-circular velocity component which was set equal to $\sigma^2_{rv} = (20)^2$, and both combined so that

$$\sigma^2 = \sigma^2_v + \sigma^2_{rv}$$ (12)

The resulting $\chi^2$ surface is plotted in Figure 7 as a function of black hole mass and inclination. The cross identifies the minimum value, $\chi^2_{min} = 22$, which occurs for a black hole mass equal to $7 \times 10^7 M_\odot$ and a disk inclination of 14 degrees. The shaded areas identify the region enclosed by the 3 $\sigma$ and 1 $\sigma$ contours which, for a two parameter fit to the data, correspond numerically to the $\chi^2_{min} + 9.21$ contour and the $\chi^2_{min} + 2.30$ contour,
respectively (Wall 1996). The boundary of the 1 σ contour (68% confidence level) leads to
the following uncertainties for the black hole mass, \( M_{BH} = (7.0^{+2}_{-1}) \times 10^7 M_\odot \), and the disk
inclination, \( i = 14 \pm 2 \) degrees. The error bars shrink slightly if \( \sigma_{rv} \) is set to 15 km/s instead
of 20 km/s. So, the quoted errors are the more conservative values.

It is gratifying that the inclination for the gas disk yielded by the model fitting agrees
well with the visual impression provided by Figure 4, that the inner H\( \alpha \) disk is only slightly
inclined. A quantitative measurement based on the ellipticity of isophotes fitted to the
H\( \alpha \) image at a radius of 0.2 arc seconds (see Figure 4) in both the original resolution and
Lucy de-convolved images (see section 4.3) yielded an average value of 16\( \pm \)5 degrees for the
inclination.

The impact of the stellar mass to light ratio, \( [M/L]_V \), on the mass derived for the
nuclear black hole was investigated. Changing, \( [M/L]_V \) from the nominal value of 4.0 to 4.5
and 3.5, which represent plausible upper and lower bounds to the stellar mass to light ratio,
resulted in no measureable change in the location of \( \chi^2_{min} \), identified by the cross in Figure
7.

The actual mass to light ratio in the central 0.1\( '' \), calculated using the deprojected
stellar mass listed in Table 3, converting that to a stellar luminosity assuming \( M/L = 4 \),
and dividing the luminosity by the black hole mass yields \( M/L \sim 500 M_\odot / L_\odot \). If one was
not persuaded by the necessity for a black hole, and instead forced the mass to light ratio
to be the value expected for stars in the central 0.1\( '' \), then the deprojected central surface
brightness would be very bright, 9.5 mag/(sq. arc sec), which is 5.3 magnitudes brighter
than anticipated from the observed bulge surface brightness profile (see section 4.2), and,
perhaps more importantly, 3.5 magnitudes brighter than actually observed with HST (see
Figure 3). So, the evidence for a black hole in M81 is rather compelling under the present
circumstances.
5. Discussion

5.1. The Prevelance of Massive Black Holes in Galaxy Nuclei, and the $M_{BH}$, $L_{bulge}$, $\sigma$ Correlation

In addition to M81, there are three galaxies in the Local Group; the Milky Way (Genzel et al. 1997; Ghez et al. 1998), M31 (Kormendy & Bender 1999), and M32 (van der Marel et al. 1998; Joseph et al. 2001) suspected of harboring massive nuclear black holes. Furthermore, another nearby galaxy, NGC 5128 at a distance of 3.5 Mpc (Hui et al. 1993), is a luminous peculiar elliptical galaxy with a nuclear radio source and radio lobes that extend to $\sim 250$ kpc (Cooper, Price, & Cole 1965). The "AGN paradigm" posits that all AGN are powered by accretion onto massive black holes, a position that is certainly supported by existing measurements of black hole masses in AGN’s (Ferrarese & Merritt 2000). Consequently, we assume that NGC 5128 also has a central massive black hole. The late-type spiral M33 is an exception, as an upper limit of 3000 $M_{\odot}$ (Merritt & Ferrarese 2001) to 1500 $M_{\odot}$ (Gebhardt et al. 2001) has been placed for a central black hole in this galaxy. The failure to detect a black hole in M33 may be due to the fact that rather than a bulge, it has a young central star cluster that is more like a globular cluster than a bulge (Gebhardt et al. 2001). Collectively, one would conclude from the evidence, based on a census of galaxies in and near the local group, that at least all bright galaxies with a bulge, or a spheroidal population, host a central massive black hole.

The apparent correlation between black hole mass and bulge luminosity (Kormendy & Richstone 1995), and the better correlation between black hole mass and bulge velocity dispersion (Peterson 1993, 2001; Ferrarese & Merritt 2000; Gebhardt et al. 2000a; Merritt & Ferrarese 2001; Ferrarese et al. 2001), suggests that all galaxies with a bulge will host a massive black hole. The $M_{BH} - \sigma_{bulge}$ correlation suggests that the growth of the bulge and the central $M_{BH}$ are physically linked. Given these correlations, our measurement of
M81’s black hole mass is almost exactly that predicted from M81’s bulge luminosity $L_{\text{bulge}} = 5.44 \times 10^9 L_\odot$ and bulge velocity dispersion if one adopts the value $\sigma = 165 \pm 10 \text{ km/s}$, measured by Pritchet (1978).

5.2. The Efficacy of Emission Line Spectroscopy

Our measurement of $(7.0_{-1}^{+2}) \times 10^7 M_\odot$ for the mass of the black hole in M81 is quite a bit higher than previous estimates based on the so called virial mass, which is calculated from the width of the broad emission lines and an estimate for the size of the broad line emitting region. Applying the virial method to the broad H$\alpha$ line, Peimbert & Peimbert (1981) set an upper limit of $1.8 \times 10^7 M_\odot$ for the mass of the black hole in M81. Using a similar argument, but applied to the broad ultra-violet lines, Ho, Fillipenko & Sargent (1996) find the black hole mass in M81 to be no greater than $3 \times 10^6 M_\odot$. Regretably, no estimates are provided for the uncertainties associated with the virial masses which precludes a judgement of their reliability. On the other hand, the limitations of the gas kinematic approach are well understood.

The realization that non-circular motions ultimately limit the precision with which gas velocities can be used to constrain the mass of the black hole in M81 is perhaps not entirely unexpected, as earlier studies (Goad 1974, 1976) cited similarly chaotic behaviour for the H$\alpha$ emitting gas in M81, albeit on a larger spatial scale, with non-circular velocities comparable to and even exceeding those reported here. Although the magnitude of the non-circular velocities is small (cf Figure 6), they are significant relative to the observed velocities because of M81’s particular combination of black hole mass, distance, and nearly face-on geometry for the inner gas disk.

The kinematics of the ionized gas in the nuclear disks in NGC 4261 (Ferrarese, Ford
& Jaffe 1996), NGC 6251 (Ferrarese & Ford 1998) show evidence for warps (changes in inclination and line of nodes) from the edges to the center of the disks. In this regard M81 is no exception. Zooming in from 100pc towards the nucleus one can see the disk inclination change from 40° to 14° and the major axis twist from a position angle of 0° to 146°. Indeed, the almost face-on aspect found for the inner ionized gas disk is a remarkable endorsement of the standard interpretation for Seyfert spectra (eg (Osterbrock 1989)), as spectroscopically, M81 is a Seyfert 1 for which one would anticipate a nearly face-on accretion disk surrounding the nuclear black hole. One of the advantages of emission line spectroscopy over alternative methods for measuring black hole masses is that this method does yield the important additional information concerning the inclination of the gas disk orbiting the nucleus.

Maciejewski and Binney (2001) describe an elegant method that breaks the degeneracy between black hole mass and disk inclination for a single slit measurement in some special cases. However, a two dimensional map is still the minimum required to correctly identify the kinematic line of nodes. Moreover, even a two-dimensional map may not be sufficient to break the degeneracy between black hole mass and disk inclination if significant non-circular velocities are present. This is particularly true in galaxy nuclei where the velocity amplitudes are small, as would be expected for low inclination disks, because in these galaxies the circular disk velocities may be comparable in magnitude to the non-circular gas velocities, and may render different models statistically indistinguishable in the $\chi^2$ plot, which was almost the case for M81.

5.3. Variability in M81

The double-peaks in the broad component of the H$\alpha$ emission line detected with the now de-commissioned Faint Object Spectrograph (FOS) during Cycle 5 (Bower et al. 1996)
are less prominent in the most recent STIS spectrum, adding further evidence for optical variability in M81 (see Figure 8). Although the variability is most apparent in the shape of the broad wings of the $\text{H}\alpha$ profile, it may be evident in the integrated broad line flux as well. The total broad line flux integrated over the map shown in Figure 5 corresponds to $(2.88 \pm 0.01) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ which is a factor of 2 higher than estimated by Bower et al. (1996) and a factor of 2.8 higher than measured by (Ho, Fillipenko & Sargent 1996). The large difference is surprising given the fact that 15 years of ground based monitoring has failed to elucidate any significant evidence for variability in M81 (Ho, Fillipenko & Sargent 1996). However, the wide range in the existing measurements may reflect the equally wide range of instruments used to obtain them, suggesting the need for a systematic monitoring campaign with a single instrument, preferably STIS, in order to pin down the extent of the variability in M81 once and for all.

Variability in low luminosity AGNs is not a very well characterized phenomenon but it is an important one to study. By analogy with the more luminous Seyferts, it has been shown that variability monitoring can lead to some very powerful results, including the mass of the black hole and the structure of the broad-line region using reverberation-mapping techniques (Blandford & McKee (1982), Netzer & Peterson (1997), Peterson (1993)). Thus, variability may lead to an independent estimate for the mass of the black hole in M81.

STIS has already been employed to measure the mass of the black hole in M81 using gas kinematics (this paper) and a measurement from stellar dynamics might be possible (Bower et al. 2000). M81 may also prove to be a good candidate for reverberation mapping if continuum variability can be established. Then M81 would be the only galaxy for which all three techniques currently employed for determining black hole masses have been applied, allowing a useful comparison of the relative merits of each.
It is of interest, therefore, to consider the requirements for a reverberation mapping program. The size of the broad line region in M81, estimated from certain emission line ratios, is $\sim 10^{16}$ cm (Peimbert & Peimbert (1981), Ho, Fillipenko & Sargent (1996)). Thus, the continuum source in M81 would need to vary on timescales of $\sim 2$ days (half the light crossing time) for a future reverberation mapping program to be viable. However, it remains to be established if the continuum does vary on such timescales and further, that it is correlated with the already established spectral line variability.
6. Conclusions

The two dimensional velocity field of the central 10pc of M81 was mapped during Cycle 7 with STIS aboard the HST. The velocity of the $\lambda_o = 6585.28$ [NII] line could be measured with confidence over the central 0.9 x 0.4 arc sec region. The resulting observed velocity field revealed the unambiguous signature of rotation with a velocity amplitude in excess of that expected from stars. The observations were compared with a kinematic model for the line emitting gas in M81 in order to constrain the mass of the black hole and the inclination of the disk spinning around it. A $\chi^2$ minimization procedure revealed evidence for significant non-circular velocities in the nuclear region of M81 which ultimately limit the precision with which the mass of the black hole can be measured to be $(7.0^{+2}_{-1}) \times 10^7 M_\odot$ with an inclination of $14 \pm 2$ degrees for the disk.

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This manuscript was prepared with the AAS LaT\TeX{} macros v5.0.
Fig. 1.— (Top) STIS spectrum of the nucleus of M81. The dashed line represents a fit to the narrow component of the H$\alpha$ emission line, the two [NII] emission lines, the two [SII] lines, the [OI] line and the underlying continuum. The corresponding fluxes are summarized in Table 1. (Bottom) The broad H$\alpha$ emission line following subtraction of the narrow emission.
Fig. 2.— (left) Observed velocity field in the central 10pc of M81. North is up, East is to the left. The axes indicate the angular scale in arc seconds. The contour spacing is 10 km/s. (right) Model velocity field for a black hole mass of $7.0 \times 10^7 M_\odot$, a position angle of 146 degrees for the kinematic line of nodes and an inclination of 14 degrees for the disk.
Fig. 3.— M81 Visual surface brightness profile from combined ground based and space based photometry. The open circles illustrate the consequence of subtracting a point source from the nucleus of M81. The solid line represents the extrapolation of an $r^{1/4}$ law into the nucleus.
Fig. 4.— The deconvolved WFPC2 image showing the Hα disk in M81 for the area measured by STIS. North is up, East is to the left. The axes indicate the angular scale in arc seconds. The contours are logarithmically spaced by 0.3 dex.
Fig. 5.— The STIS line spread function as characterized by the intensity of the broad component of the Hα emission line in M81. North is up, East is to the left. The axes indicate the angular scale in arc seconds. The contours are logarithmically spaced by 0.3
Fig. 6.— The non-circular velocities in M81 as evidenced by the difference between the data and a model velocity field for a black hole mass of $7.0 \times 10^7 M_\odot$, a position angle of 146 degrees for the kinematic line of nodes and an inclination of 14 degrees for the disk (see Figure 2). North is up, East is to the left. The axes indicate the angular scale in arc seconds.
Fig. 7.— The chi-square surface illustrating the quality of the model fit to the observed two dimensional velocity field as a function of black hole mass and disk inclination. The cross identifies the location of $\chi^2_{\text{min}} = 22$, corresponding to a black hole mass of $7.0 \times 10^7 M_\odot$ and a disk inclination of 14 degrees. The regions enclosed by the 1σ and the 3σ contours are shaded. The next contour is at $\chi^2 = 40$, and the contour interval is 32 for all subsequent contours.
Fig. 8.— Time variable Hα profiles in M81. The solid line in both panels is the Cycle 7 STIS spectrum (This paper). Left Hand Panel: comparison with the ground based spectrum of Ho et al. 1996. Right Hand Panel: comparison with the HST FOS spectrum of Bower et al. 1996.
Table 1. Line Parameters for the Nuclear Spectrum

<table>
<thead>
<tr>
<th>Line</th>
<th>Central Wavelength (Å)</th>
<th>Flux (10^{-14} erg cm^{-2} s^{-1})^a</th>
<th>FWHM (km/s)</th>
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<td>OI</td>
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<td>NII</td>
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<tr>
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<tr>
<td>SII</td>
<td>6732.39 ± 0.1</td>
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</tbody>
</table>

^aContinuum subtracted, but not corrected for dust extinction.

^bThe broad Hα emission line was not fit with a gaussian, see text for details.
Table 2. Observed Wavelengths for the Vacuum Wavelength 6585.28 [NII] Emission Line

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<tr>
<th>$x''$</th>
<th>$y''$</th>
<th>$\lambda(\AA)$</th>
<th>$x''$</th>
<th>$y''$</th>
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Note. — Wavelengths measured for the vacuum wavelength 6585.28 [NII] emission line. The columns are arranged by slit position, east is left and north is up. The typical 1σ uncertainty in the wavelength measurements is ± 0.1 Å which corresponds to a 1σ velocity uncertainty of ± 5 km/s.
Table 3. Deprojected Nuclear Masses

<table>
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<tr>
<th>R (&quot;)</th>
<th>s^a</th>
<th>M^*(s)^b</th>
<th>M(R)/M_☉^c</th>
<th>R(pc)</th>
<th>V(R) (km/s)</th>
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</table>

^a_s = R/r_c

^bM^*(s) from Young 1976

^cdeprojected mass interior to R