DYNAMICS OF THE NARROW-LINE REGION IN THE SEYFERT 2 GALAXY NGC 1068

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ABSTRACT

We present dynamical models based on a study of high-resolution long-slit spectra of the narrow-line region (NLR) in NGC 1068 obtained with the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope (HST). The dynamical models consider the radiative force due to the active galactic nucleus (AGN), gravitational forces from the supermassive black hole (SMBH), nuclear stellar cluster, and galactic bulge, and a drag force due to the NLR clouds interacting with a hot ambient medium. The derived velocity profile of the NLR gas is compared to that obtained from our previous kinematic models of the NLR, using a simple biconical geometry for the outflowing NLR clouds. The results show that the acceleration profile due to radiative line driving is too steep to fit the data and that gravitational forces alone cannot slow the clouds down, but with drag forces included, the clouds can slow down to the systemic velocity over the range 100–400 pc, as observed. However, we are not able to match the gradual acceleration of the NLR clouds from ~0 to 100 pc, indicating the need for additional dynamical studies.

Subject headings: galaxies: individual (NGC 1068) — galaxies: kinematics and dynamics — galaxies: Seyfert — ultraviolet: galaxies

1. INTRODUCTION

Recent studies of the kinematics of the narrow-line regions (NLRs) of Seyfert galaxies have taken advantage of the high resolution of the Hubble Space Telescope (HST) to map the velocities of these regions. (Evans et al. 1993; Macchetto et al. 1994; Hutchings et al. 1998; Nelson et al. 2000; Crenshaw et al. 2000; Crenshaw & Kraemer 2000b; Ruiz et al. 2001, 2005; Cecil et al. 2002; Das et al. 2005, 2006, and references therein). Although there have been a number of papers on the dynamical aspects of the NLR, most of these studies relied on ground-based data limited to spatial resolutions of ≥50 pc for even the most nearby active galactic nuclei (AGNs; see Kaiser et al. 2000, and references therein). These studies relied primarily on spatially integrated line profiles to understand the dynamics of the NLR (Schulz 1990; Veilleux 1991), but the problem arose that the emission-line profiles of the NLR can be explained by many different types of dynamical models, such as infall, rotation, and outflows (Capriotti et al. 1980, 1981; Vrtilek 1983, 1985; Krolik & Vrtilek 1984).

With the launch of HST and its high angular resolution (~0.1″), the NLRs of Seyfert galaxies have received considerable attention. With the limited long-slit capability of the faint object camera (FOC), and later the expanded capability of STIS, detailed constraints on the kinematics of the NLRs in Seyfert and other galaxies became possible. In turn, these kinematic studies have provided good diagnostics on which dynamical analyses can be based.

1.1. Previous Kinematic Studies of the NLRs of Seyfert Galaxies

The structure of the NLR resembles a bicone, as expected from a simple unified model of Seyfert galaxies, due to collimation by a thick torus (Antonucci & Miller 1985). Both Schulz (1990) and Evans et al. (1993) have modeled the NLR of NGC 4151 and found it to be consistent with a biconical geometry. In an HST study done on a sample of Seyfert 1 and 2 galaxies, Schmitt & Kinney (1996) compared both Seyfert types to study their NLR morphologies, and found triangular structures in most of their Seyfert 2s and circular structures in most of their Seyfert 1s, consistent with the unified model and biconical structure for the NLR (see also Schmitt et al. 2003a, 2003b). Veilleux et al. (2001) modeled the inner regions of the Seyfert galaxy NGC 2992 and found that the ionized gas can be fitted with a biconical structure.

We have recently completed a study of the kinematics of the NLRs in two Seyfert galaxies (Das et al. 2005, hereafter Paper I; Das et al. 2006, hereafter Paper II). Since our dynamical work in this paper is a direct extension of the works of those two papers, we summarize their results below. In Paper I, kinematic models were developed to match the emission-line velocities from high-resolution STIS spectra within ~400 pc of the central black hole of the Seyfert 1 galaxy NGC 4151. The NLR gas showed strong evidence of acceleration from ~0 pc out to ~100 pc, then deceleration back to systemic velocity at ~400 pc, with velocity roughly proportional to distance in each case. The maximum velocity of the outflowing gas at the turnover point (96 pc) was ~800 km s⁻¹ relative to the black hole. Based on our kinematic model, the NLR could be represented by a bicone with inner and outer half opening angles of 15° and 33°, respectively, and inclination of ~45° with respect to the plane of the sky, consistent with previous kinematic work done on NGC 4151 with different slit positions (Crenshaw et al. 2000). Some of the fainter NLR clouds showed evidence of backflow at the point where the clouds turned over in their velocities. The radio jet was found to have little effect on the kinematics of the NLR clouds; however, there was some evidence of radial velocity splitting of the fainter NLR clouds near bright knots in the radio jet. The brighter clouds were not accelerated by the jet.

In Paper II, we developed a similar model for the Seyfert 2 galaxy NGC 1068, again with high-resolution spectra taken with the STIS aboard HST. With seven parallel slit positions covering the entire NLR, we extracted radial velocity profiles and matched them with our newly developed three-dimensional biconical models. Our kinematical models showed that the NLR gas accelerated out to ~140 pc (the turnover point), then decelerated...
back to systemic velocity at a distance of \( \sim 400 \) pc from the central black hole. The maximum velocity of outflow of the gas was \( \sim 2000 \) km s\(^{-1}\) with respect to the black hole, and the model predicted inner and outer half opening angles of the bicone of 20° and 40°, respectively, and an inclination of 5° out of the plane of the sky. We used high-resolution radio maps of the NLR obtained from Gallimore et al. (2004) to search for jet-cloud interactions. Evidence showed that, similar to NGC 4151, the fainter NLR clouds were split near bright knots in the radio jets, whereas the brighter NLR clouds remained unaffected by the jet.

Other Seyfert galaxies show flow patterns similar to those of NGC 4151 and NGC 1068, such as the Seyfert 2 galaxy Mrk 3 (Ruiz et al. 2001, 2005). The radial velocities of these galaxies were matched with a common kinematic model with little variation in the parameter space, which begs the question, what are the physical processes involved that would cause such a similar flow pattern in both types of Seyfert galaxies? Is this question that motivated us to carry out this dynamical study.

1.2. Previous Dynamical Studies of the NLRs of Seyfert Galaxies

In the first truly dynamical model of the NLR based on HST kinematics, Everett & Murray (2007) attempted to fit the NLR velocities in NGC 4151 based on measurements done in Paper I. They tested an isothermal Parker wind model, which assumes thermally expanding winds (Parker 1965). By assuming a spherical cloud geometry, they let the Parker wind drag along the embedded NLR clouds. As the Parker wind accelerates by thermal expansion and slow cooling, the clouds are also accelerated to high speeds. They then let the Parker wind run into a low-density ambient medium to slow the velocity of the wind, and hence the clouds, to the systemic velocity. The model explains the velocity profile of the NLR of NGC 4151, but suffers from the fact that an isothermal wind cannot be sustained out to large distances. Also, the mass profile of the SMBH plus galaxy, which determines the temperature profile for their model, is not exactly known for NGC 4151. Hence, while their model was not successful on physical grounds, it is worth noting its relative success in matching the NLR kinematics.

In this paper, the main question we want to address is how we can constrain the dynamics of the NLR in Seyfert galaxies with the detailed knowledge that we have gained from our kinematic studies. Here, we concentrate on the dynamics of the NLR in NGC 1068, since it has the best constraints. We start with a simple construction of the enclosed-mass function based on data from previous studies and eventually formulate a radiation pressure–gravity tug-of-war on the NLR clouds. The questions we attempt to answer include the following. (1) If the NLR gas is in outflow, is radiation pressure really the best driving mechanism? (2) If the NLR gas is turning over its velocity and decelerating back to systemic, is gravity responsible for stopping the gas? (3) Can we fit the velocity profile of the data with a simple radiation–gravity law, or do we need to include another force (such as drag)?

Our analysis applies to NGC 1068 in particular, but has relevance to all Seyferts in general that show signs of gas outflow and subsequent deceleration (Ruiz et al. 2005). To test whether gravity is playing any role in stopping and turning back the gas velocity, we construct a mass profile within \( \sim 10,000 \) pc from the nucleus of NGC 1068. With the mass profile in hand, we test whether the gas kinematics are dominated by rotation. Such a test might prove fruitful to match the velocity field in NGC 4151, which shows redshifts northeast and blueshifts southwest of the nucleus, but from a geometrical point of view, this test will present much difficulty when applied to the velocity field of NGC 1068, which shows blueshifts and redshifts on each side of the nucleus. Next we plot the escape velocity against distance to see if the gas should escape or not, given the velocities seen in the data, and whether or not the kinematics of the NLR can be dominated by gravitational infall. Then we concentrate on outflow, assuming spherical symmetry and pure radial motion. First we determine whether the deceleration of the gas can be attributed to the enclosed mass, regardless of the outward accelerating force. We then apply radiative line driving plus gravitational forces and compare the results to the observed velocity law of NGC 1068 derived from the kinematic models. Finally, we introduce a drag force due to an ambient medium on the NLR clouds, in addition to radiation pressure and gravity, to determine whether it can improve the fit to either the accelerating or decelerating portions of the observed velocity curve.

2. BUILDING THE MASS PROFILE

In building a model of the enclosed mass as a function of distance from the central SMBH, we incorporate various sub-systems into our mass profile. These include contributions from the SMBH, the nuclear stellar cluster, and the bulge. For all these systems, we assume spherical symmetry, for simplicity. We have assumed that the stellar cluster and bulge extend all the way inward to the SMBH, which may overestimate the mass close in. The size of the stellar cluster was estimated to be \( \sim 140 \) pc, based on a study by Thatte et al. (1997), and the bulge was assumed to extend up to \( 10,000 \) pc. Mass contribution from the galactic disk of NGC 1068 was neglected because the galactic potential is dominated by the large bulge to at least \( 1000 \) pc, well beyond the extent of the NLR.

2.1. The Black Hole Mass

NGC 1068 is one of only a few AGNs that shows an edge-on disk of \( \text{H}_2\text{O} \) maser emission close to the SMBH. The disk shows the signature of a rotational velocity curve, which can be used to determine the mass of the SMBH. Greenhill & Gwinn (1997) estimated the mass of NGC 1068 to be \( 1.5 \times 10^7 \, M_\odot \) within 0.65 pc, based on the velocity field of the \( \text{H}_2\text{O} \) maser emission observed with the Very Long Baseline Array (VLBA) and the Very Large Array (VLA). We will therefore use this estimate for the mass of the SMBH.

2.2. The Bulge Mass

Since we are going out to \( \sim 10,000 \) pc, which encloses the NLR and the extended NLR clouds, we need an accurate assessment of the total mass within this region. At small distances (\( \lesssim 1 \) pc), the SMBH is dominant, although in the case of NGC 1068, a concentrated stellar cluster is also providing substantial gravity close in. For an estimate of the bulge mass in NGC 1068, we rely on the work of Häring & Rix (2004). They found a tight correlation between black hole mass and bulge mass for a sample of 30 galaxies, including NGC 1068. They determined the bulge mass by modeling the bulge with the Jeans equation in spherical form. They assumed the bulge to be isotropic and spherically symmetric, which might lead to an overestimation of the bulge mass; however, they also neglect any contribution from dark matter, which would tend to underestimate the bulge mass. Their value for the bulge mass in NGC 1068 is \( 2.3 \times 10^{10} \, M_\odot \) within a radius \( r = 3R_e \) (3 effective radii), where \( R_e = 3.1 \pm 0.8 \) kpc, a value taken from the surface brightness deconvolution of Marconi & Hunt (2003). The effective radius \( R_e \) is defined to be such that half of the total light from the galaxy is predicted to be contained within the isophotal ellipse that has area \( \pi R_e^2 \) (Binney & Merrifield 1998).
Elliptical galaxies’ and bulges’ surface brightnesses can be well described by the empirical formula developed by de Vaucouleurs (1948)

\[ I(R) = L_e e^{-7.6692[(R/R_e)^{1/4} - 1]}, \]

where \( L_e = I(R_e) \). In the 1980s and 1990s, a family of stellar density curves emerged that modeled both elliptical galaxies and bulges well. These curves are of the form

\[ \rho(r) = \frac{(3 - \gamma)M}{4\pi r^3(r + \eta)^{4-\gamma}}, \tag{2} \]

where \( \eta \) (in pc) is a scaling radius and \( M \) is the total mass of the bulge (Dehnen 1993). The parameter \( \gamma \) determines different types of models, where \( \gamma = 2 \) corresponds to previous density models by Jaffe (1983), and \( \gamma = 1 \) to models by Hernquist (1990). These models, when integrated over a spherical volume, yield the enclosed mass

\[ M(r) = \int_0^r 4\pi r^2 \rho(t) dt = \frac{4\pi(3 - \gamma)M\eta}{4\pi} \int_0^r t^{2} dt = \frac{r^3}{12} M \left( \frac{r}{r + \eta} \right)^{3-\gamma}. \tag{3} \]

For the special case \( \gamma = 1.5 \), the density profile of equation (2) yields a surface density distribution that closely matches the de Vaucouleurs surface brightness profile of equation (1), to within 15\% over nearly four decades in radius (Dehnen 1993). Therefore, we adopt the following form of the mass function as the bulge profile:

\[ M(r) = M \left( \frac{r}{r + \eta} \right)^{1.5}. \tag{4} \]

We find a suitable value for \( \eta \) in equation (4) by first defining the “half-mass radius” \( r_{1/2} \):

\[ \frac{1}{2} M = M \left( \frac{r_{1/2}}{r_{1/2} + \eta} \right)^{3/2}, \tag{5} \]

which yields the following relation for \( \eta \)

\[ \eta = r_{1/2} (2^{2/3} - 1). \tag{6} \]

Dehnen (1993) has found a simple approximation for \( R_e/r_{1/2} \) that depends only slightly on \( \gamma \). For \( \gamma \leq 5/2 \), he found that

\[ \frac{R_e}{r_{1/2}} \approx 0.7549 - 0.00439\gamma + 0.00322\gamma^2 - 0.00182\gamma^3 \pm 0.0007. \tag{7} \]

Therefore, we can find a value for \( \eta \) by using \( \gamma = 1.5, R_e \) given above, and equation (6). We find that \( \eta \approx 2400 \) pc. We also know that \( M(3R_e) = 2.3 \times 10^{10} \, \odot \), so that

\[ M = 2.3 \times 10^{10} \left[ \frac{3(3.1 \times 10^3)}{3(3.1 \times 10^3) + 2400} \right]^{1.5} = 3.2 \times 10^{10} \, \odot. \tag{8} \]

The bulge mass distribution can finally be written as

\[ M(r) = 3.2 \times 10^{10} \left( \frac{r_{pc}}{r_{pc} + 2400} \right)^{1.5} \, \odot. \tag{9} \]

2.3. The Nuclear Stellar Cluster Mass

It is known that NGC 1068 has a compact nuclear stellar cluster \( \sim 140 \) pc in radius (Thatte et al. 1997; Crenshaw & Kraemer 2000a), which contributes significant mass to the total mass profile of the NLR of NGC 1068. Therefore, this mass must be taken into account when deriving the mass profile. Thatte et al. (1997) found a mass of \( 6.8 \times 10^8 \, \text{M}_\odot \) within \( 1'' \) of the SMBH of NGC 1068, assuming a virialized, isotropic, and isothermal distribution of the stars. They used the stellar velocity distribution \( (\sigma_r) \) found in Dressler (1984), a value of \( 143 \pm 5 \) km s\(^{-1}\) at \( \sim 1'' \), to calculate the total dynamical mass within \( 1'' \) of the nucleus of NGC 1068.

\[ M_{\text{dyn}} = \frac{2\sigma_r^2R}{G}, \tag{10} \]

where \( R = 1'' \approx 72 \) pc for NGC 1068. This mass includes contributions from the stellar cluster, the nucleus, and the bulge within a radius of 72 pc. Therefore, to find just the mass from the stellar cluster, \( M_{\text{sc}} \), we took out the rest of the mass contribution from the total mass:

\[ M_{\text{sc}}(72 \text{ pc}) = M_{\text{dyn}}(72 \text{ pc}) - M_{\text{SMBH}} - M_{\text{bulge}}(72 \text{ pc}). \tag{11} \]

Making the various substitutions, we have

\[ M_{\text{sc}}(72 \text{ pc}) = 6.8 \times 10^8 - 1.5 \times 10^7 \]

\[ -3.2 \times 10^{10} \left( \frac{72}{72 + 2400} \right)^{1.5} = 5.1 \times 10^8 \, \text{M}_\odot. \tag{12} \]

Based on the radial surface brightness profile presented in Figure 4 of Thatte et al. (1997), Beckert & Duschl (2004) computed a power law consistent with the form \( S_r(r) \propto r^{-1} \) to fit the data. They claim that if the profile traces the stellar mass distribution, then they would expect that the mass profile would have the form \( M_{\text{sc}}(r) \propto r^5 \) given a spherical, isothermal distribution of stars in the cluster. Using their distribution, we can estimate the stellar mass function based on the condition \( M_{\text{sc}}(72 \text{ pc}) = 5.1 \times 10^8 \, \text{M}_\odot \), so that \( k = (5.1 \times 10^8)/72 = 7.1 \times 10^6 \, \text{M}_\odot \text{ pc}^{-1} \). The stellar cluster mass function is therefore

\[ M_{\text{sc}}(r) = 7.1 \times 10^6 r_{pc} \, \text{M}_\odot. \tag{13} \]

Beyond the observed extent of the stellar cluster, we assume that \( M_{\text{sc}}(r) \) is constant. Finally, the total enclosed mass function for the NLR of NGC 1068 is given by \( M_{\text{tot}}(r) = M_{\text{SMBH}} + M_{\text{bulge}} + M_{\text{sc}} \), or

\[ M_{\text{tot}}(r) = 1.5 \times 10^7 + 7.1 \times 10^6 r_{pc} \]

\[ + 3.2 \times 10^{10} \left( \frac{r_{pc}}{r_{pc} + 2400} \right)^{1.5} \, \text{M}_\odot. \tag{14} \]

3. DYNAMICS BASED ON GRAVITY

A figure representing the total mass enclosed within \( r_{pc} \) is shown in the top panel of Figure 1. The mass profiles for each contribution, the SMBH, bulge, and cluster are also shown in the figure.
Close to the nucleus, the nuclear stellar cluster dominates up to its entire extent, while the bulge takes over from there. The black hole mass dominates at $\lesssim 2$ pc. The kink in the total mass curve at $\sim 140$ pc is because the stellar cluster was cut off abruptly at this location. We could have modeled the cluster to assume an exponential drop-off after 140 pc, but this would not have contributed much to the gravitational force exerted by the total mass.

### 3.1. Rotation

With the total mass profile, we calculate the circular rotational velocity and plot it as a function of distance, as shown in the middle panel of Figure 1. The rotation velocity only depends on the enclosed mass at radius $r_{\text{pc}}$ and is given by the formula

$$V(r) = \sqrt{\frac{G M(r)}{r}};$$

(15)

For demonstration purposes, we show the rotational velocities as if only each mass component were present, as well as the velocity for the total mass profile. The rotational velocity profile indicates that rotation cannot dominate the kinematics of the NLR of NGC 1068, because many observed data points exhibit large velocities ($\geq 1000$ km s$^{-1}$), whereas the rotation curve never exceeds $\sim 220$ km s$^{-1}$ at large distances (100 pc). Again, the stellar cluster dominates the velocities up to $\sim 300$ pc.

### 3.2. Escape and Infall Velocity

The escape velocity at a given distance $r_{\text{pc}}$ is calculated numerically from the formula

$$V(r) = \sqrt{\int_{r}^{\infty} 2G \frac{M(t)}{t^2} \, dt \, \text{km s}^{-1}};$$

(16)

based on the enclosed mass function, and is plotted in the bottom panel of Figure 1. According to our kinematic model, the maximum velocity at the turnover radius $r_t = 140$ pc is $2000$ km s$^{-1}$ (Paper II); therefore, Figure 1 tells us that the NLR clouds should have escaped after 140 pc, where the escape velocity is only $\sim 500$ km s$^{-1}$. In the data, however, clouds at 140 pc are at velocities much higher than escape velocity; yet after the turnover point, the clouds start to decrease their velocity and return to systemic. Thus, some force other than gravity is causing the clouds to decelerate at $r \geq 140$ pc. The infall velocity profile is equivalent to the escape velocity profile, except that the velocity vector is now directed inward. Therefore, gravitational infall cannot account for the faster moving clouds at 140 pc, and in general does not match the observed velocity profile (Paper II).

### 3.3. Gravitational Drag

To test the importance of the force of gravity alone on slowing down the outflowing NLR clouds, we give the clouds a maximum velocity at the turnover point and let gravity do the rest. In other words, we assume that there is no outward driving force after the turnover point and let the clouds coast under the force of gravity. The top panel of Figure 2 shows that with a maximum velocity $\leq 1000$ km s$^{-1}$ at 140 pc, there is little deceleration with radius. However, with maximum velocities $\leq 300$ km s$^{-1}$, gravity can slow the clouds down to rest, as seen in the bottom panel of Figure 2. The maximum velocities in the NLRs of some Seyfert galaxies are on the order of $\sim 400$ km s$^{-1}$ (Ruiz et al. 2005), and gravitational deceleration may be important in these cases. The kinematic model of NGC 1068, however, shows maximum velocities of up to $\sim 2000$ km s$^{-1}$, clearly out of the reach of...
gravitational deceleration. Gravity alone cannot slow down the outflowing clouds in this case, so there must be some other force or forces involved.

To compound the problem, suppose we let radiation or some other force push on the gas while gravity is trying to pull it back. In this case, the gravitational deceleration will be even less. However, to really drive the gas out efficiently, we need to incorporate other sources of opacity, such as bound-bound and bound-free opacity, in addition to those from Thomson scattering. These additional opacities are included via the force multiplier $M$ in equation (17), which is primarily a function of the ionization parameter $U$ for a given spectral energy distribution (Crenshaw et al. 2003, and references therein).

The acceleration due to gravity per mass is simply given by

$$a(r) = -\frac{GM(r)}{r^2},$$

where $a$ is the acceleration, $L$ is the bolometric luminosity of NGC 1068, $\sigma_T$ is the Thomson scattering cross section for the electron, $r$ is the distance, $c$ is the speed of light, $m_p$ is the mass of the proton, and $M$ is the force multiplier. As mentioned above, to really drive the gas out efficiently, we need to incorporate other forces push on the gas while gravity is trying to pull it back. In this case, the gravitational deceleration will be even less. However, to really drive the gas out efficiently, we need to incorporate other sources of opacity, such as bound-bound and bound-free opacity, in addition to those from Thomson scattering. These additional opacities are included via the force multiplier $M$ in equation (17), which is primarily a function of the ionization parameter $U$ for a given spectral energy distribution (Crenshaw et al. 2003, and references therein).

The acceleration due to gravity per mass is simply given by

$$a(r) = -\frac{GM(r)}{r^2},$$

where $M(r)$ is the total enclosed mass within $r$ pc and $G$ is the universal gravitational constant. Putting equations (17) and (18) together, we have

$$a(r) = \frac{L\sigma_T M}{4\pi r^2 m_p} - \frac{GM(r)}{r^2}. \quad (19)$$

Now we have to rewrite the acceleration in terms of velocity as a function of radius, and then solve for $v(r)$:

$$a = \frac{dv}{dt} = \frac{dr}{dt} \frac{dv}{dr} = v \frac{dv}{dr}. \quad (20)$$

Therefore, we can now write equation (19) as the simple separable differential equation

$$v \frac{dv}{dr} = \frac{L\sigma_T M}{4\pi r^2 m_p} dr - \frac{GM(r)}{r^2} dr. \quad (21)$$

4. RADIATION-GRAVITY FORMALISM

The various mechanisms to push the gas out from close to the nucleus include a radiation-pressure-driven wind, a thermally driven wind, or a magnetohydrodynamic (MHD) wind (Crenshaw et al. 2003). The latter two methods are discussed in more detail in Everett (2005) and Everett & Murray (2007), and were summarized in § 1.2. However, no dynamical model to date has led to a satisfactory description of the kinematics in NGC 1068 or NGC 4151. The radiation-driven wind mechanism is most efficient when the momentum imparted to the gas is due to line-driving (bound-bound transitions), although bound-free and free-free electron transitions (Thomson scattering) also contribute to driving the gas out (Chelouche & Netzer 2001). The radiation force is dependent on the ionization state of the gas, with lower ionization states more efficient due to the greater availability of electrons in the bound states. If dust is mixed in with the NLR gas, then it will compete with the gas in absorbing ionizing photons, and hence radiation pressure on the dust can become an important contributor to the velocities of the outflowing gas in the NLR (Dopita et al. 2002). If the dust grains are electrically charged, they can drag the ionized gas along to similar velocities as the dust. In this section, we ignore the effects of dust, which would only increase the radiative acceleration. Thus we consider a radiation-driving mechanism coupled with the effects of gravity to find the velocity profile of the NLR gas.

4.1. Building the Velocity Equation

We start with the acceleration due to radiation on a point mass,

$$a(r) = \frac{L\sigma_T M}{4\pi r^2 m_p}, \quad (17)$$

where $a$ is the acceleration, $L$ is the bolometric luminosity of NGC 1068, $\sigma_T$ is the Thomson scattering cross section for the electron, $r$ is the distance, $c$ is the speed of light, $m_p$ is the mass of the proton, and $M$ is the force multiplier. As mentioned above, to really drive the gas out efficiently, we need to incorporate other sources of opacity, such as bound-bound and bound-free opacity, in addition to those from Thomson scattering. These additional opacities are included via the force multiplier $M$ in equation (17), which is primarily a function of the ionization parameter $U$ for a given spectral energy distribution (Crenshaw et al. 2003, and references therein).

The acceleration due to gravity per mass is given by

$$a(r) = -\frac{GM(r)}{r^2}, \quad (18)$$

where $M(r)$ is the total enclosed mass within $r$ pc and $G$ is the universal gravitational constant. Putting equations (17) and (18) together, we have

$$a(r) = \frac{L\sigma_T M}{4\pi r^2 m_p} - \frac{GM(r)}{r^2}. \quad (19)$$

Now we have to rewrite the acceleration in terms of velocity as a function of radius, and then solve for $v(r)$:

$$a = \frac{dv}{dt} = \frac{dr}{dt} \frac{dv}{dr} = v \frac{dv}{dr}. \quad (20)$$

Therefore, we can now write equation (19) as the simple separable differential equation

$$v \frac{dv}{dr} = \frac{L\sigma_T M}{4\pi r^2 m_p} dr - \frac{GM(r)}{r^2} dr. \quad (21)$$

4. The ionization parameter $U$ is defined as $U = (\int L_{\nu} d\nu d\nu d\nu) / 4\pi r^2 n_H c$, which is equal to the number of ionizing photons divided by the number of hydrogen atoms at the ionized face of the clouds, where $h\nu_0 = 13.6$ eV and $n_H$ is the hydrogen number density.
Substituting for the constants in equation (21) and converting to appropriate units of km s\(^{-1}\) and pc, then integrating and setting the initial velocity to zero yields the following form for \(v(r)\):

\[
v(r) = \sqrt{\int_{r_1}^{r_2} \left[ 6840L_{44} \frac{M}{r^2} - 8.6 \times 10^{-3} \frac{M(t)}{r^2} \right] dt},
\]  

(22)

where \(L_{44}\) is luminosity in units of \(10^{44}\) ergs s\(^{-1}\) and \(M(r)\) is in units of \(M_\odot\). The constraints on the luminosity and the force multiplier are presented in the next section.

4.2. Physical Constraints on the NLR of NGC 1068

Since NGC 1068 is a Seyfert 2 galaxy, we cannot measure its luminosity directly. From Pier et al. (1994), the total luminosity of NGC 1068 is given by

\[
L_{bol} = 2.2 \times 10^{44} \left( \frac{f_{\text{refl}}}{0.01} \right)^{-1} \left( \frac{D}{22 \text{ Mpc}} \right)^2 L_\odot,
\]  

(23)

where \(f_{\text{refl}}\) is the fraction of nuclear flux observed as scattered radiation, \(D\) is the distance to NGC 1068, and \(L_\odot\) is the solar luminosity. The most uncertain term in equation (23) is \(f_{\text{refl}}\). Pier et al. (1994) have summarized a range of values for \(f_{\text{refl}}\) that have been determined previously by several authors. The range in \(f_{\text{refl}}\) spans a few orders of magnitude, from 0.001 to 0.05. They claim that the best estimate comes from Miller et al. (1991), who had determined a value for \(f_{\text{refl}}\) of 0.015, based on observations of [O \text{ III}] and broad H\(\beta\) luminosity and their ratio. Pier et al. (1994) concluded that \(f_{\text{refl}}\) is probably within a factor of a few of 0.01: hence we have adopted a value for \(f_{\text{refl}}\) of 0.015 because it is the “best” estimate and close to the average value adopted by Pier et al. (1994). We already know the distance to NGC 1068 as 14.4 Mpc (Bland-Hawthorn et al. 1997), so the bolometric luminosity of NGC 1068 is given by

\[
L_{bol} = 2.2 \times 10^{44} \left( \frac{0.015}{0.01} \right)^{-1} \left( \frac{14.4}{22 \text{ Mpc}} \right)^2 L_\odot
\]

\[
= 2.4 \times 10^{44} \text{ ergs s}^{-1},
\]  

(24)

a value which could be uncertain by a factor of 0.3–15, depending on \(f_{\text{refl}}\).

The emission lines arising from the NLR gas are best fitted with a two-component photoionization model at each position, based on HST/STIS long-slit spectra (Kraemer & Crenshaw 2000). According to Kraemer & Crenshaw, the ionization state of the gas ranges from \(U \sim 10^{-1.5}\) to \(10^{-3.6}\) for the two components, but seems to vary with distance. Using \(U\) and the spectral energy distribution for NGC 1068, we found the force multiplier to vary from \(M \approx 500\) to 6000 for the front face (ionized face) of the clouds, based on CLOUDY models (Ferland et al. 1998). The mass function was derived in previous sections, and \(L_{44}\) was 2.4, so we can now numerically solve equation (22) for \(v(r)\), assuming that \(M\) is constant with distance. The results are presented in the next section.

4.3. Radiation and Gravity Results

Equation (22) has only two parameters that we can vary to find the velocity \(v\) as a function of distance \(r\): the launch radius \(r_1\) and the force multiplier \(M\). We plotted \(v(r)\) for various combinations of launch radii and force multipliers of the gas. The top panel of Figure 3 shows that with a launch radius of \(r_1 = 1\) pc, the velocity of the gas increases with the force multiplier, but quickly reaches a terminal velocity and does not slow down significantly.
DYNAMICS OF THE NLR IN NGC 1068

5. RADIATION, GRAVITY, AND DRAG FORCES

The radiation-gravity interaction on the NLR clouds of NGC 1068 fails to reproduce its velocity profile. For reasonable parameters, the velocity quickly increases close to the nucleus and mostly remains constant over large distances, regardless of launch radius. The maximum outflow velocity is rather sensitive to launch radius and decreases with increasing \( r_1 \), but the clouds’ velocities never turn over and decrease. Fine-tuning \( r_1 \) and \( M \) outside of the range of reasonable parameters can lead to a deceleration profile, but the resulting velocity profile and amplitude does not match the observed trend. Therefore, we conclude that there must be additional forces at play in the NLR to account for the velocity profile that we see in the data. One such force that could explain the trend in the data is drag, whereby the clouds are slowing down in a more diffuse, hotter, and higher ionization medium (Crenshaw & Kraemer 2000b).

5.1. Deceleration Due to Drag

The drag force exerted on a cloud by an ambient medium is

\[
F_{\text{drag,cloud}} = \rho_{\text{med}}(v_{\text{cloud}} - v_{\text{med}})^2 A_{\text{cloud}},
\]

where \( \rho_{\text{med}} \) is the mass density of the ambient medium, \( v_{\text{cloud}} \) and \( v_{\text{med}} \) are the velocities of the cloud and medium, respectively, and \( A_{\text{cloud}} \) represents the cross sectional area of a cloud (Everett & Murray 2007). Following Everett & Murray, we assume the clouds to be spherical with mass \( m_{\text{cloud}} = 4/3 \pi R_{\text{cloud}}^3 \rho_{\text{cloud}} \), where \( R_{\text{cloud}} \) is the radius of a cloud, and \( \rho_{\text{cloud}} \) is its mass density. The acceleration on the clouds due to drag is then

\[
a_{\text{drag,cloud}} = \frac{\rho_{\text{med}}(v_{\text{cloud}} - v_{\text{med}})^2}{4/3 \pi R_{\text{cloud}}^3 \rho_{\text{cloud}}} \times \frac{3}{2} \left( v_{\text{cloud}} - v_{\text{med}} \right)^2,
\]

where \( n \) is the hydrogen number density and \( m_p \) is the mass of the proton. In our case, we assume that the velocity of the ambient medium is zero and the radius of the cloud remains constant. Therefore, with \( v_{\text{med}} \approx 0 \) we can write

\[
a_{\text{drag,cloud}} = - \frac{n_{\text{med}}}{N_{\text{H,cloud}} 4/3 \pi R_{\text{cloud}}^3} \cdot \frac{3}{2} \left( v_{\text{cloud}} - v_{\text{med}} \right)^2,
\]

where \( N_{\text{H,cloud}} = n_{\text{cloud}} R_{\text{cloud}} \) is the hydrogen column density of the cloud and the minus sign represents deceleration. Combined with the radiative and gravitational acceleration of equation (19), the total acceleration on the clouds becomes

\[
a_{\text{tot}} = \frac{L_4 \sigma T M}{4 \pi r^2 c m_p} - \frac{GM(r)}{r^2} - \frac{n_{\text{med}}}{N_{\text{H,cloud}}} 3 \pi R_{\text{cloud}}^3 \left( v_{\text{cloud}} - v_{\text{med}} \right)^2,
\]

which in differential form is

\[
v dv = \frac{L_4 \sigma T M}{4 \pi r^2 c m_p} dr - \frac{GM(r)}{r^2} \frac{dr}{vr^2} - \frac{n_{\text{med}}}{N_{\text{H,cloud}}} 3 \pi R_{\text{cloud}}^3 \left( v_{\text{cloud}} - v_{\text{med}} \right)^2 dr.
\]

Substituting the various constants and converting to units of pc and km s\(^{-1}\), we have the following inseparable differential equation to solve:

\[
\frac{dv}{dr} = \frac{3420 L_4 \sigma T M}{\pi r^2 c m_p} - 4.3 \times 10^{-3} \frac{GM(r)}{r^2} - 2.3 \times 10^{-2} \frac{n_{\text{med}}}{N_{20}} v(r),
\]

where \( N_{20} = N_{\text{H}}/10^{20} \) cm\(^{-2}\).

5.2. Constraints on Cloud and Medium Densities for NGC 1068

Both NGC 1068 and NGC 4151 show evidence for highly ionized gas extended throughout their NLRs, based on Chandra X-ray Observatory images (Ogle et al. 2000, 2003). Thus, we assume an ambient medium that is highly ionized, with ionization parameter \( U \approx 10 \). The ionization parameter, which is inversely related to the density and radius, can be written as

\[
U \propto \frac{\int_{r_0}^{\infty} L_{\nu} / \nu \ dv}{r^2 n_{\text{H}}}.
\]

Therefore, if the ambient medium and the NLR clouds see the same ionizing luminosity (\( L_{\text{ion}} \)) at a particular distance \( r \) from the source, we can write

\[
n_{\text{med}} = \frac{n_{\text{cloud}} U_{\text{cloud}}}{U_{\text{med}}}.
\]

Kraemer & Crenshaw (2000) provided good constraints on the parameters on the right side of equation (32). The densities of the NLR clouds are almost constant out to large distances from the nucleus, with a typical value of \( n_{\text{cloud}} \approx 10^3 \) cm\(^{-3}\) for clouds with \( U_{\text{cloud}} \approx 10^{-3} \). If we substitute these estimates in equation (32), we will have a typical estimate for \( n_{\text{med}} \):

\[
n_{\text{med}} = 10^4 \frac{10^{-3}}{10} = 1 \text{ cm}^{-3}.
\]

Kraemer & Crenshaw found column densities for the NLR clouds in the range \( N_{\text{H}} = 10^{19} - 10^{21} \) cm\(^{-2}\), which corresponds to \( N_{20} = 0.1-10 \). Since we are interested in the ratio \( n_{\text{med}}/N_{20} \), varying
either parameter while keeping the other constant will result in the same curves. In this paper, we choose to keep $N_{20}$ constant at the average value of 1 and vary $n_{\text{med}}$, because $n_{\text{med}}$ is the most unknown quantity. We already know that $M$ can take values from 500 to 6000, so equation (30) can now be solved numerically for $v(r)$, with various values of the launch radius $r_1$, force multiplier $M$, and ratio $n_{\text{med}}/N_{20}$. We used Mathematica v5.2, which employs the most efficient choices among various flavors of Runge-Kutta algorithms, to solve for $v(r)$. The results are presented in the next section.

5.3. Radiation, Gravity, and Drag Results

The top panel of Figure 4 presents several plots with a force multiplier of 500, a launch radius of 1 pc, and varying medium densities $n_{\text{med}}$ shown by the numbers. Bottom: The velocity profiles for a force multiplier of 6000, a launch radius of 20 pc, and varying medium densities similar to the top panel.

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5.3. Radiation, Gravity, and Drag Results

The top panel of Figure 4 presents several plots with a force multiplier of 500, a launch radius of 1 pc, a column density of $N_{20} = 1$, and various densities for the ambient medium. The figure shows that when launched at 1 pc, the gas accelerates to a maximum velocity inside 10 pc, then slows down again. The velocity slows down faster with increasing drag forces, as measured by increasing densities of the ambient medium. However, the point of maximum velocity is too close in to match the data, which has a turnover velocity at ~140 pc. The curve with medium density $n_{\text{med}} = 0.33$ shows gradual deceleration out to ~500 pc, but its maximum velocity is slightly too high. Any other curve has either too high of a velocity at turnover or a velocity that drops too quickly. Note that the velocity for the data that we are trying to match is ~2000 km s$^{-1}$ at a turnover of ~140 pc for NGC 1068. With force multipliers higher than 500, the same trend as in Figure 4 is seen in the velocity model, except that the velocities are much higher ($\geq$6000 km s$^{-1}$). Again, the curve that seems to best match the deceleration part in the data is with medium density $n_{\text{med}} = 0.33$. The rest of the curves decelerate too quickly or too slowly. The major problem with all of these curves is that the velocity turnover point is much closer to the nucleus than 140 pc.

Another way to decrease the overall velocity is to increase the launch radius and tweak the force multiplier and ambient density. We tried a launch radius of 10 pc with force multipliers ranging from 500 to 6000. The maximum velocity drops as expected, reaching ~700 km s$^{-1}$ for a force multiplier of 500 and climbing to ~2500 km s$^{-1}$ as we increase the force multiplier to 6000. We noticed that the turning point increases by a factor of 5 as we increase the launch radius from 1 to 10 pc. However, the turnover point is still too low to fit the data well. In order to have a good fit, we first need to maximize the launch radius and then tweak the force multiplier and medium density to get the closest match to the data as possible.

The resolution in our data is ~10 pc, and we should not launch much beyond this distance, since we see clouds close to the SMBH with near zero velocity. Therefore, in the bottom panel of Figure 4, we present a plot with a launch radius of $r_1 = 20$ pc, a force multiplier of 6000, and a column density of $N_{20} = 1$. The maximum velocity reached is ~1700 km s$^{-1}$ with $n_{\text{med}} = 10$. The best curve to represent the data seems to be the one with $n_{\text{med}} = 0.33$, whose maximum velocity is ~1500 km s$^{-1}$, although the turnover point at ~60 pc is still too low according to our kinematic model. Furthermore, we have had to tweak the launch radius and force multiplier to very specific values, such that only a narrow range of the observed values gives a reasonably decent fit. However, to directly test this velocity profile, we generate biconical models similar to our previous kinematic models (Paper II) to determine whether a more dynamical velocity law, rather than the simple linear law, can reasonably match the data.

Fig. 4.—Top: Velocity profiles for a force multiplier of 500, a launch radius of 1 pc, and varying medium densities $n_{\text{med}}$ shown by the numbers. Bottom: The velocity profiles for a force multiplier of 6000, a launch radius of 20 pc, and varying medium densities similar to the top panel.

Fig. 5.—Model of slit 4, generated with input parameters from Table 1 and the best-fit velocity profile from the bottom panel of Fig. 4 with $n_{\text{med}} = 0.33$. Clearly this model is a poor match to the data.
TABLE 1

| Parameter          | Value |
|--------------------|-------|
| z_{max} (pc)       | 450   |
| \theta_{inner} (deg) | 10    |
| \theta_{outer} (deg) | 40    |
| \iota_{axis} (deg)  | 5     |
| PA_{axis} (deg)     | 57.8  |
| v_{low}             | Equation (30) |

NOTE—Shown in Fig. 5. z_{max} is the distance from the center to one end of the bicone. \theta_{inner} is the inner opening angle of the bicone. \theta_{outer} is the outer opening angle of the bicone. \iota_{axis} is the inclination of the bicone axis out of the plane of the sky, with positive inclination implied by the north bicone closer toward the observer. PA_{axis} is the position angle of the bicone axis in the plane of the sky. v_{low} is the velocity law used in mapping the velocity field onto the bicone.

5.4. Dynamical Fit

We applied our kinematic models of Paper II with our dynamical velocity law to the data. Previously we had used a simple kinematic velocity law based on the relation \( v = kr \). Now we instead substitute the velocity relation based on equation (30), which represented a more physical situation. A model with the new velocity law of equation (30) is presented in the top panel of Figure 5, using the input parameters from Table 1 and the best-fit curve from Figure 4, with \( N_{20} = 1 \) and \( n_{med} = 0.33 \). Our biconical model was constructed with an inner and outer half opening angle of 10° and 40°, respectively, an inclination of 5°, a position angle of 57.8°, and a half-size of 450 pc. Points on the bicone were assigned velocities according to equation (30). The center slit (slit 4; see Paper II) is used here for comparison. We extracted the velocities from the model at a position equivalent to slit 4, and those are shown in the shaded regions in the top panel of Figure 5. The data from slit 4 are shown with triangles.

The model represents a poor fit to the data from slit 4 (the center slit) of NGC 1068. This was expected from looking at the previous velocity plots, as the turnover point was too low, the launch radius was a bit large, and the velocity profile did not resemble our kinematically derived linear profiles. We have varied the input parameters from Table 1, but this makes very little improvement. The turnover point, starting distance, and maximum velocity of the bicone cannot be varied without changing the drag parameters, as these are implicitly defined in equation (30). The thickness of the bicone can be increased to accommodate more data points, but the bicone will show lots of unnecessary shaded regions. Changing the maximum extent of the bicone, \( z_{max} \), will have absolutely no effect on the shaded region, except for interrupting the shaded regions before, or continuing them beyond, \( \pm 6^\circ \). That leaves us with only two parameters to vary, the inclination of the bicone axis and its position angle in the sky, and varying these two alone did not fix the model.

6. CONCLUSIONS

With radiation pressure driving the NLR clouds, their velocities will accelerate very quickly within a few parsecs of the nucleus, assuming the clouds are indeed launched close in. With the introduction of the drag forces, the overall velocities are lowered, but even so, the velocities reach the maximum too quickly. The data suggest that the clouds are gradually increasing their velocities to a maximum at about 140 pc. This gradient in the velocity cannot be simply accounted for by radiative forces driving the clouds. It seems, therefore, that radiation pressure may not be the only driving mechanism for the NLR clouds, or that other forces are involved to steer the clouds to that particular gradient. The velocity profile shown in the data resembles one with a linear or "Hubble flow" law. The inclusion of a drag force only serves to reduce the overall high velocities due to radiation driving, but the maximum velocities are reached very close to the nucleus, too close to match the data effectively.

Gravitational forces alone cannot stop the fast moving clouds observed in the NLR of NGC 1068. With velocities as high as 1500 km s\(^{-1}\) at 140 pc, the clouds should have escaped the NLR. To compound the problem, when radiation forces are added, the cloud velocities are boosted even more. Yet we see clouds that are slowing down and gradually reaching systemic velocity. Therefore, the data suggest that there is a powerful force dragging on the clouds to slow their velocity.

The drag force that we introduce can have a significant effect on the clouds' velocities. We can therefore conclude that the drag forces are a strong competitor to the radiative forces, strong enough to bring the clouds to a halt even close to the nucleus, depending on the column densities of the outflowing clouds and the density of the ambient medium. However, the overall velocity profiles generated with radiative, gravitational, and drag forces do not match the data for NGC 1068. Assuming that the mass profile of NGC 4151 is similar to the one for NGC 1068, it will prove difficult to match its observed velocity profile because the same linear trends are seen in the velocity of the outflowing clouds. The same can be said for Mrk 3 (Rui et al. 2001).

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