Kinematics of the Narrow-Line Region in the Seyfert 2 Galaxy Markarian 3

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Abstract

We present measurements of radial velocities for the narrow-line region gas in the Seyfert 2 galaxy Mrk 3 out to \( \sim 1 \) kpc from the nucleus. The observations consist of two data sets, both using the Space Telescope Imaging Spectrograph on board the Hubble Space Telescope: (1) an [O III] slitless spectrum with the G430M grating of the inner 3" around the nucleus and (2) a long-slit observation centered on the nucleus (P.A. = 71\(^\circ\)) by using the G430L grating and the 52" \( \times \) 0.1 aperture. Our analysis produces radial velocity maps of the emission-line gas, which indicate trends in the gas motion. These include blueshifts and redshifts on either side of the nucleus, steep velocity rises from systemic up to \( \pm 700 \) \( \text{km s}^{-1} \) taking place in the inner 0.3 (0.08 kpc) both east and west of the nucleus, gradual velocity descents back to near-systemic values from 0.3–1.0, slightly uneven velocity amplitudes on each side of the nucleus, and narrow velocity ranges over the entire observed region. When fitted to kinematic models for the NLR gas, the data clearly favor one in which the gas exists in a partially filled bicone, is accelerated radially away from the nucleus, and is followed by a constant deceleration (possibly due to collision with an ambient medium). This geometry and general kinematic model are in agreement with previous work done on the NLR gas of NGC 1068 and NGC 4151. On scales of hundreds of parsecs, we conclude that radial outflow may be a common feature of Seyfert galaxies.

Key words: galaxies: individual (Markarian 3) — galaxies: Seyfert

1. Introduction

In many Seyfert 2 galaxies, narrow-line region (NLR) clouds appear to lie in a biconical or roughly linear configuration surrounding the nucleus (Schmitt & Kinney 1996; Pogge 1989; Evans et al. 1991). Various kinematic models have been proposed to explain NLR cloud motion. Capetti et al. (1995) have compared optical and radio measurements of the NLR of Mrk 3 and concluded that the NLR clouds are the result of radio jet plasma expanding away from the bicone axis. Winge et al. (1997, 1999) postulate gravitational motions for the NLR in NGC 4151. Recently, Crenshaw & Kraemer (2000, hereafter C2000a) and Kaiser et al. (2000) have determined radial velocities as a function of position in the NLRs of NGC 1068 and NGC 4151 (the brightest Seyfert 2 and Seyfert 1 galaxies, respectively) with the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (HST). C2000a have proposed a model for both Seyfert galaxies in which clouds within an evacuated bicone are radially accelerated from the nucleus by wind pressure or radiation pressure, encounter and collide with an ambient medium, and then decelerate to near-systemic values. This model explains the trends seen in the radial velocity as a function of position in the inner kiloparsec around the nuclei of these galaxies.

Mrk 3 is a well-studied Seyfert 2 galaxy, which shows evidence for a hidden Seyfert 1 nucleus from broad polarized emission lines (Schmidt & Miller 1985; Miller & Goodrich 1990; Tran 1995). The host galaxy type is classified as S0 (de Vaucouleurs et al. 1991). It lies 53 Mpc away \((H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}, z = 0.0135, 3'89 \text{ kpc}^{-1})\) and has been studied in every wavelength regime, from the X-ray (Griffiths 1998; Georgantopoulos et al. 1999) through the radio (Kukula et al. 1999). Mrk 3 has bright [O III] emission-line clouds that lie in a biconical configuration (the apex of the two cones is coincident with the nucleus) along P.A. = 80\(^\circ\), with a half-opening angle of 22:5 (Schmitt & Kinney 1996). At the end of the western cone, a large diffuse knot appears, while on the end of the eastern cone, a bright knot appears out of the bicone, giving the entire structure an S shape (Capetti et al. 1995). Schmitt & Kinney (1996) measure the clouds as extending 280 pc on either side of the nucleus. Recent X-ray observations of Mrk 3 using Chandra (Sako et al. 2000) have found soft X-ray extended emission, which lies along this position angle. Radio jets have also been observed (Kukula et al. 1993, 1999) along the same position angle; these appear to follow the biconical structure, although the half-opening angle is far less \(\sim 8°–10°\). The jets also have an S shape (though much less pronounced) in the same regions as the [O III] emission. Though the radio knots lie close to the emission-line clouds, they are not exactly coincident; Capetti et al. (1999) suggest that they lie along the convex edge of the S-shaped curvature.

A fainter set of clouds, situated along P.A. \(\sim 100°\), are seen farther out in the extended narrow-line region (ENLR). These clouds extend from 1'0 on either side of the nucleus to about 3'2. This group is more diffuse, is fainter in surface...
brightness by an order of magnitude, and follows the \([\text{O \textsc{iii}}]\) emission contour lines seen in the ground-based observations of Pogge & De Robertis (1993).

In this paper, we present two \textit{HST} spectra (one long-slit, one slitless) of the Mrk 3 NLR clouds. They provide consistent values of radial velocities as functions of NLR cloud positions. The two data sets are then fitted to a kinematic model that provides a radial velocity map of clouds within a bicone, given a velocity law that directs their motion. When fitted to a radial acceleration plus constant deceleration velocity law, the trends seen in both data sets are matched well. In § 2 we detail the observations, while the data analysis is presented in § 3. The results from the two data sets are given in § 4. The discussion of the model is given in § 5, with § 6 providing the overall discussion. Section 7 presents the conclusions.

2. OBSERVATIONS

To find the NLR knots in the slitless observations, and hence, determine their velocities, a companion \([\text{O \textsc{iii}}]\) image, as well as a continuum image, are required. To that end, the archival images of Mrk 3 were obtained. The first of these is a Wide Field Planetary Camera (WFPC) \([\text{O \textsc{iii}}]\) observation. This image served to match the bright NLR clouds. A Wide Field Planetary Camera 2 (WFPC 2) continuum image was also retrieved, as well as a Faint Object Camera (FOC) \([\text{O \textsc{iii}}]\) image. The FOC image is shown in Figure 1. It served to match the faint ENLR clouds. A summary of all the observations is given in Table 1.

The new slitless observations take advantage of STIS's spatial resolution (0.1') and the G430M spectral resolution (\(\lambda/\Delta \lambda \approx 10,000\)). The observations were centered at 5093 Å, with a bandwidth of 286 Å. In addition to \([\text{O \textsc{iii}}]\) \(\lambda 5007\), \([\text{O \textsc{iii}}]\) \(\lambda 4959\) and \(\text{H} \beta\) were also observed. The spectral region around \([\text{O \textsc{iii}}]\) \(\lambda 5007\) is shown in Figure 2. The dispersion is along the horizontal axis, while the spatial direction is along the vertical axis. The bright NLR clouds are smeared out along the dispersion axis. They are also shifted along this axis, from which their radial velocities can be calculated. The faint ENLR clouds are also seen with apparently smaller dispersions.

We also obtained long-slit observations of Mrk 3 using the G140L, G230L, G430L, and G750L gratings and the 52'' \( \times \) 0.1' aperture. The complete observations cover the wavelength range from 1150–10000 Å. A full analysis of these data will be presented separately (Collins et al. 2001).

![Figure 1](image-url)  
**Fig. 1.**—FOC image of the bright NLR clouds of Mrk 3. The position of the long slit is seen to pass through the nucleus and through the clouds in spots. The cross depicts the position of the nuclear continuum center. The backward S shape of the main clouds is seen.
For this work, the single emission line of \([\text{O III}]\) \(\lambda 5007\) from these observations was used. The slit had a position angle of 71° and was chosen to pass through the nucleus. The position of the long-slit is shown in Figure 1, overlaid on the FOC image for comparison with the [O III] clouds.

3. DATA ANALYSIS

The data reduction was done with IDL software developed for the STIS Instrument Definition Team at Goddard Space Flight Center (Lindler et al. 1999). The spectral images were cleaned of cosmic rays during the image processing. Once the archival images were retrieved, they were also cleaned of cosmic rays. Determining radial velocities of NLR clouds using slitless spectra has been done previously using NGC 4151 (Hutchings et al. 1998; Kaiser et al. 2000). These authors describe the STIS slitless data analysis; a brief synopsis follows here.

The data analysis consists of matching [O III] undispersed clouds (from an FOC, WFPC, or WFPC2 image) with their counterparts in an STIS-dispersed image. To make the one-to-one correspondence between clouds, the non-STIS images must be rotated, aligned, and corrected for anamorphic magnification with respect to the STIS image (spatial scale of 0.0507 pixel\(^{-1}\)). Once the spatial scale is set, then the wavelength scale (ultimately a velocity scale) must be set using the calibration spectra. To set the velocity scale, the direct [O III] images are aligned with the STIS dispersed image such that there is no shift for a cloud.

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**Table 1**

| Date       | Instrument | Root Name   | Filter, Grating | Exposure (s) | Slit |
|------------|------------|-------------|-----------------|--------------|-----|
| 1991 July 18 (A)     | PC         | W0MW0601T   | F502N           | 1800         |     |
| 1992 Dec 11 (A)      | FOC        | X14W0301T   | F501N           | 1197         |     |
| 1997 Oct 20 (A)      | WFPC2      | U2E62A01T   | F606W           | 500          |     |
| 2000 Jan 16 (N)      | STIS       | O5F403010   | Clear           | 20           | Open|
| 2000 Jan 16 (N)      | STIS       | O5F403020   | G430M           | 2154         | Open|
| 2000 Aug 22 (N)      | STIS       | O5KS01010   | G430L           | 1080         | 52'' x 0.1 |

\(^{a}\) (A) archival; (N) new.

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**Figure 2**—STIS slitless spectrum showing the region around \([\text{O III}]\) \(\lambda 5007\). The horizontal axis is along the dispersion, while the vertical scale is the spatial axis. The clouds are shifted slightly along the dispersion axis; the shift allows the radial velocity to be calculated. The fainter ENLR clouds can also be seen \(\sim 1''\) above and below the NLR.
at the systemic redshift \((z = 0.0135; \text{Tiift \& Cooke 1988})\) of Mrk 3. The redshifted wavelength is taken from 21 cm measurements of H I, assumed to be at rest with respect to the central galactic region. We note that the WFPC [O iii] observation and WFPC 2 continuum image were taken at different times. Despite this, we were able to identify the corresponding bright distinct emission-line knots in both images.

Once the STIS dispersed image and the non-STIS undispersed image are aligned, Gaussian fits are made to the NLR knots in both images on each row parallel to the dispersion axis. This is to accurately determine the positions and FWHMs for each knot. The difference in position (in pixels) between an undispersed and dispersed knot is converted to a difference in angstrom units, then to one in velocity. The difference in width (in quadrature) gives the velocity dispersion of the emission knot. For some purposes, the individual line measurements are averaged over each cloud to obtain a single value of radial velocity and dispersion, and the standard deviations are used as uncertainties.

For the long-slit data, Gaussian fits are made to the NLR knots on each row perpendicular to the dispersion (in 0.05 intervals). Once the positions and FWHMs are determined, the radial velocities and dispersions for each row are calculated using the same routines as for the slitless spectrum. The FWHMs were corrected for the instrumental broadening of 300 km s\(^{-1}\). For the purpose of comparing slitless and long-slit data, we determined from their position angles which clouds lay in the slit. We then averaged the long-slit radial velocities for these clouds over each individual cloud, thus obtaining two values of radial velocity from the two different methods, and plotted them against each other. For both sets of radial velocities, the standard deviations calculated were used for the uncertainties. Figure 3 shows averaged slitless radial velocities plotted against the corresponding averaged long-slit radial velocities. The plot shows very good agreement, to within \(\sim 50\) km s\(^{-1}\), indicating that there are no systematic errors with the slitless technique.

4. RESULTS

The entire data set is seen in Figure 4, which shows a plot of radial velocity versus distance. Each point represents an average over each cloud. The inner region clouds, defined here as clouds from 2\arcsec west of the nucleus to 1\arcsec east of the nucleus, are seen to have a wide range of radial velocities \((-1000\) to +600 km s\(^{-1}\)). Roughly equal numbers of clouds show redshifts and blueshifts. As noted in the previous section, the long-slit cloud values are consistent with the slitless spectral values, both in terms of location and velocity. The fainter, ENLR clouds stretch for about 2\arcsec farther out in either direction than the inner region clouds. The fainter clouds show a narrower range of radial velocity, from +400 down to \(-200\) km s\(^{-1}\), with the majority of the clouds (75%) showing redshifts.

Figure 5 shows the binned velocity distribution of all the clouds. The inner region clouds are difficult to distinguish because of their proximity to each other, so we present this figure to show the ENLR clouds. The eastern half of these clouds is exclusively redshifted, while the majority of the western half is so with lower magnitudes. Figure 6 is an expanded view of the central region of Figure 5 to show the inner region clouds' velocity distribution in greater detail. The inner region clouds, in contrast to the extended region clouds, have equal numbers of blueshifted and redshifted clouds on either side of the nucleus. The blueshifted clouds to the east tend to have higher velocities, while to the west the velocities are similar for redshifts and blueshifts. On either side, maximum values of radial velocities are reached \(\sim 0\farcs3\) away from the center for both sets of data.

Figure 7 shows the unbinned NLR radial velocities (relative to systemic) plotted against distance from the optical continuum center. The unbinned velocities are used for the model to take advantage of the spatial resolution of \textit{HST}. Long-slit points are shown, along with the slitless spectral points that lie within the slit. The velocity errors are only measurement errors in this case and are comparable to the size of the symbols. The two sets of data points are seen...
to be compatible. They show properties that must be duplicated by any model fit. We briefly discuss each of these properties.

Both sets of data points show rapid increases in velocities with respect to the projected radius (from systemic values at the nucleus to about $\pm600$ km s$^{-1}$) out to near systemic values. The amplitudes range from $\sim300$ km s$^{-1}$ on the blueshifted west side to $\sim800$ km s$^{-1}$ on the blueshifted east side (ignoring a few high-velocity points). This variation in amplitude implies that any fitted cone is tilted, and in fact the angle of inclination can be calculated by the amplitude difference. Finally, the range of velocities is fairly narrow. For example, $\sim0^\circ.30$ west of the nucleus, blueshifted velocities are seen exclusively from $[-200$ to $-300]$ km s$^{-1}$, while redshifted velocities are seen spanning a narrow range from 400 to 500 km s$^{-1}$. At this distance, no velocities are seen from $[-200$ to $400]$ km s$^{-1}$. Any model must be able to match these narrow velocity ranges.

5. MODEL FITTING

Once the spatial orientations and radial velocities of the clouds were obtained, we attempted to fit these observations by using kinematic models. The program calculates the projected radial velocities and simulates a spectral line of material on the surface of a thin disk, or a bicone, either filled or hollow. The material can assume one of various velocity laws that control its motion. We concentrate here on the NLR out to $D^\circ.30$ on either side of the nucleus. Later, we will discuss briefly the ENLR clouds and their motion.

We can immediately rule out gravitational models as a major factor in the kinematics by calculating the mass required to impart radial velocities on the order of $500$–$1000$ km s$^{-1}$ at a distance 100–200 pc away from the nucleus. This mass is of the order of $(10^6$–$10^8) M_\odot$. Typical masses for black holes in Seyfert nuclei are $(10^6$–$10^8) M_\odot$ (e.g., Peterson & Wandel 2000). The observed morphology of the NLR does not suggest a disk geometry, and the redshifts and blueshifts on either side of the nucleus cannot be the result of simple Keplerian rotation. Thus, in the NLR, we may conclude that the gravitational potential of the black hole plays a minor kinematic role. As we move farther out into the stellar gravitational component, gravitational forces may play a larger role in the kinematics.

The bicone model has been used previously to describe the NLR emission-line clouds of NGC 1068 and NGC 4151 (2000a; Crenshaw et al. 2000, hereafter C2000b). The two cones (one on either side of the nucleus) are assumed to possess identical properties, including geometry, size, and
velocity law. In addition, the cones are assumed to have a filling factor of 1 within the minimum and maximum half-opening angle and not to absorb [O III] photons. We adjust certain parameters to obtain the best fit. The program creates a two-dimensional velocity map, which is sampled through a simulated slit. We applied the models to unbinned velocities to obtain the best spatial resolution.

We briefly describe some of the model parameters. These are listed, for reference, in Table 2. The model fits the radial velocity data to a series of nested bicones, with the apices centered on the nucleus. The height of each cone is given by $D$. Nesting the bicones gives a minimum and maximum half-opening angle ($\theta_{\text{min}}$ and $\theta_{\text{max}}$). Because of the range of half-opening angles, a corresponding range of velocities at different distances is produced, which is shown by the program as a shading or envelope. The inclination angle, $i$, is the angle between the bicone axis and the observer’s line of sight. A deprojected maximum velocity ($V_{\text{max}}$) is used for input as well. The NLR gas can follow one of various velocity laws, which are described below, as a function of distance.

The best fit was obtained using two factors. The first one was used for determining the optimal parameters in each velocity law. At least two-thirds of the data points had to lie within the model envelope. The second was used to distinguish the resulting best fits among all the velocity laws. It involved determining, by eye, how much of the envelope was left without data points. The more the observations filled the shading, the better the model. Since we obtained a fairly complete data set, the observational points needed to cover as much of the model fit as possible. The best-fit parameters are listed in Table 3.

Several model input variables were constrained by the imaging. The first of these was the extent of the NLR. Based on the approximate placing of a bicone on the Mrk 3 NLR by Schmitt & Kinney (1996), we measured its total extent as $\sim 2\degree$. In addition, the maximum half-opening angle was measured from the images, giving a value of $25\degree$. This agrees with Schmitt & Kinney (1996), who measure a maximum half-opening angle of $22.5\degree$. The minimum half-opening angle is not determinable, so it was varied to match the data. The optimum value for the model fit was $15\degree$. This value places the emission-line material outside the observed radio jet cone (half-opening angle $\sim 7\degree$–$8\degree$; Capetti et al. 1995).

The inclination angle was calculated based on the differences between the radial velocity maxima on the west and east sides of the cones. The maximum blueshifts are higher by $\sim 300$ km s$^{-1}$ than the maximum redshifts on the east side. The NLR inclination angle (relative to the plane of the sky) was then calculated as $5\degree$–$10\degree$, using simple trigonometry. Finally, the value for the maximum deprojected velocity of the NLR gas was chosen so that it would match the observed NLR radial velocity peak (about $-800$ km s$^{-1}$). The velocity laws of the models are summarized below.

1. The radial acceleration (RA) outflow model consists of NLR clouds being driven away from the nucleus, perhaps by winds or jets. The acceleration is along the bicones’ entire length. The best fit was not able to match the high velocities near the center, given the observed parameters. The only way to marginally match these velocities was to widen the half-opening angle past $40\degree$, but the sharp downturns cannot then be fitted. It is clear from the images that the ionization cone’s half-opening angle cannot be more than $30\degree$ (see Fig. 1). If there is acceleration along the bicone, it cannot take place along the entire length of the NLR.

2. The constant velocity (CV) model consists of clouds with a negligible drag force, having been accelerated out to some distance (small compared with the NLR), then proceeding with constant velocity. This model is able to match the high central velocities $\sim 0.3$ from the nucleus. Farther out, however, the modeled velocities remain at a constant value out to the ENLR, whereas the observed velocities drop to near systemic values by $\sim 1.0$ out from the center.

3. The constant tangential (CT) model consists of NLR clouds moving radially away from the central radio axis. This would be seen if the radio plasma expanded within the emission-line bicone. This fit resembles the CV model.

### Table 2

Model Parameters

| Parameter                                      | Symbol or Constant Value |
|-----------------------------------------------|--------------------------|
| Minimum and maximum distance of cones (pc)    | Min. = 0, Max. = $D$     |
| Minimum and maximum half-opening angle        | $\theta_{\text{min}}, \theta_{\text{max}}$ |
| Inclination angle                             | $i$                      |
| Deprojected maximum velocity of NLR gas (km s$^{-1}$) | $V_{\text{max}}$       |
| Velocity laws:                                 |                          |
| Constant velocity                             | CV                       |
| Radial acceleration                           | RA                       |
| Radial acceleration plus constant deceleration | RA + CD                 |
| Constant tangential flow                      | CT                       |
| Gravitational infall                          | GI                       |
| Center of slit                                 | Centered on optical continuum peak |
| Position angle of the long slit               | $\sim 71\degree$         |
| Slit width (pixels)                           | 0.1                      |

### Table 3

Parameters of Each Best-Fit Model

| Parameter         | CV | RA | RA + CD | CT |
|-------------------|----|----|---------|----|
| $D$ (pc)$^a$       | 80 | 80 | 80      | 80 |
| $\theta_{\text{min}}$ | 15 | 25 | 15      | 25 |
| $\theta_{\text{max}}$ | 15 | 25 | 15      | 25 |
| $i$ $^c$          | 5$^\circ$ | 5$^\circ$ | 5$^\circ$ | 5$^\circ$ |
| $V_{\text{max}}$ (km s$^{-1}$) | 1400 | 3000 | 1750 | 550 |

* Maximum extent of cones.
* Minimum and maximum half-opening angle.
* Cone inclination angle with respect to the plane of the sky.
* Deprojected maximum velocity of NLR gas.
except that it predicts equal-magnitude redshifts and blueshifts on either side of the nucleus. This is certainly not the case, as seen in the two data sets. Note that this model predicts velocity magnitudes substantially less (1/2 to 1/3) than those of the other models (see Table 3). These velocities appear to be too low. There are a number of other inconsistencies with this model, which are discussed in § 6.

4. The model that fits the most data points is the radial acceleration plus constant deceleration (RA + CD). The model can be visualized as material first accelerated by wind or radiation pressure from the nucleus, which then impacts an ambient medium and then decelerates at a constant rate. This model implies that the emission-line clouds originate from a region closer to the nucleus and move outward from there. Figure 8 shows the long-slit and slitless data points overlaid with the shading from this model. Obviously, this model does not perfectly fit every point, but it fits the gross features of the observations well. Many of the discrepant points can be ascribed to slightly different acceleration or deceleration laws in different quadrants. The discrepant high-velocity points suggest that perhaps clouds do not encounter the ambient, possibly patchy, medium or they encounter it in a region of lower density and do not decelerate as much.

6. DISCUSSION

The slitless spectral method of determining radial velocity gives consistent values with the long-slit method, as shown in Figures 3 and 7. This result gives confidence in future work using the slitless method and has been shown before for NGC 4151 (Hutchings et al. 1998; C2000b). The best-fit RA + CD model shows, in addition to fitting all the trends seen in the data, some discrepancies. These can best be explained by slightly different acceleration and deceleration laws in different directions.

While the NLR clouds are fitted most closely by the RA + CD model, the ENLR clouds require a different model. These clouds lie farther out (from 1")–3") and have radial velocities \( \lesssim 350 \text{ km s}^{-1} \). They can be seen clearly in Figure 2. They appear to be influenced by the gravitational potential of the galactic disk and bulge, rather than by the supermassive black hole. This hypothesis agrees with surface photometry on Mrk 3 done by one of us (Bower). Ellipsoids were fitted to the surface brightness of Mrk 3, from 0'01 out to 100'. From these fits, a spherical dynamical model was used to predict a rough upper limit on the rotational radial velocity induced by the gravitational potential. For the range from 1" to \( \sim 5" \), where the ENLR clouds reside, the projected radial velocities are predicted to be \( \lesssim 200 \text{ km s}^{-1} \). This heuristic result agrees roughly with the observed ENLR cloud velocities, although we cannot explain the preponderance of redshifted clouds with this model. They may be due to a lack of ionized gas at the positions that would produce blueshifts. The ENLR results also agree with a kinematic study done by Nelson & Whittle (1996). They plot the \([O \, III]\) profile line width versus the nuclear stellar velocity dispersion and determine that on scales of \(10^{2} - 10^{3} \text{ pc} \) the bulge gravitational potential plays a major role in the kinematics. The observed radial velocities seen in the ENLR of Mrk 3 seem to imply a stronger kinematic role for a bulge gravitational potential at these projected distances as well.

The orientation of the host galaxy has been previously reported as 27° out of the plane of the sky (Schmitt & Kinney 1996). If this orientation extends down to kiloparsec scales, then the plane of the galactic disk would lie within the angular range of one side of each cone (15° to 25°, tilted 5° out of the plane of the sky). The situation then resembles that of NGC 1068 and NGC 4151 (C2000a; C2000b), which also seem to have the galactic disk and one side of the bicone in the same plane. Unger et al. (1987) propose that the galactic disk’s ionization (by the nucleus) contributes to ENLR gas, and we support this conclusion. They also observe, from a sample of seven Seyfert 2 galaxies, that the ENLR gas is extended along the radio axis and the NLR gas, which we observe as well.

The radio jet and the NLR emission share a similar axis and are nearly coincident. However, other than their near spatial coincidence, there are no other correlations, as would be expected if the radio plasma’s expansion were the source of the NLR velocities. Capetti et al. (1999) obtained FOC spectra of the NLR of Mrk 3. They placed the slit in cuts perpendicular to the radio jet. Our spectra, on the other hand, are coincident with and parallel to the jet. In the points that we have in common, our radial velocities agree. They used their spectra to conclude that the expansion of the radio jet causes the NLR gas to expand outward from the radio axis (this scenario is similar to our CT model), and furthermore, in their picture the jet is inclined with respect to the host galaxy disk gas. This creates an asymmetrical expansion of the NLR gas, with the gas on the side of the jet out of the disk expanding rapidly away from the jet in their model (this inclination aspect distinguishes Capetti’s model from our CT model).

Based on our Mrk 3 data points, we cannot rule out Capetti’s asymmetric expansion model. However, we prefer the radial acceleration plus constant deceleration model for the following reasons: First, there is not a one-to-one correspondence between the NLR cloud velocities along the long slit and the positions of the radio knots. This lack of correspondence has been noted in other objects (NGC 4151; Kaiser et al. 2000), as well as this object (Kukula et al. 1999). In addition, our biconical model is able to explain the observed NLR radial velocities in NGC 4151, a Seyfert 1 galaxy, by simply tilting the bicone (C2000b). The radial
velocities seen in NGC 4151 have a range of $\pm 600$ km s$^{-1}$ relative to systemic, similar to values seen in Mrk 3. In addition, in NGC 4151, the radial velocity pattern seen is one of all blueshifts on one side of the nucleus and all redshifts on the other side (Kaiser et al. 2000). Assuming we are seeing both the near sides and the far sides of the cones (relative to the plane of the sky), this pattern cannot be reproduced by any model in which the NLR gas expands radially away from the radio jet axis. Only outflowing material will reproduce this pattern.

7. CONCLUSIONS

STIS spectra of the NLR of the Seyfert 2 galaxy Mrk 3 were obtained. Radial velocities of the emission-line gas were determined as a function of position (out to $\sim 1$ kpc from the nucleus). The velocity maps indicate trends in the gas motion. These include blueshifts and redshifts on either side of the nucleus, steep velocity increases with respect to the projected radius from systemic up to about $\pm 800$ km s$^{-1}$ taking place in the inner 0.3 (0.08 kpc) both east and west of the nucleus, and gradual velocity decreases back to near-systemic values from 0.3–1.0.

The data were then fitted to kinematic models for the NLR gas on the surface of a bicone. The data sets were fitted best with a radial acceleration plus constant deceleration model. In the model, the cones extend out to a radius of 1.0 from the nucleus, with a half-opening angle between 15° and 25°. The modeled material reaches a maximum deprojected velocity of 1750 km s$^{-1}$, reaching this velocity at a distance of 0.3–0.43 from the nucleus, close to the observed distance of 0.2–0.3 from the nucleus. The fit could be improved by positing different turnover radii and/or acceleration and deceleration laws for each quadrant. Also, the high-velocity data points not fitted by the model appear to be clouds that did not encounter any dense medium and maintained their acceleration. Nevertheless, our goal of being able to explain all the trends in the data with a simple model was accomplished. We have ruled out gravitational and constant velocity models. We show that a model in which the NLR emission is produced by expansion of radio jet plasma away from the radio axis does not fit the data well.

An important observational result is that the two distinct methods of obtaining radial velocities each gave similar results. This has been shown previously for NGC 4151 (Hutchings et al. 1998; Kaiser et al. 2000). The slitless spectral procedure of obtaining radial velocities has proved to be a useful and efficient tool for quickly examining and mapping nearby galaxies with clumpy NLRs and ENLRs. We will take advantage of this technique in the future to map the kinematics of the NLR in nine other Seyfert 2 galaxies.

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