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THE *HST* VIEW OF THE NARROW LINE REGION OF SEYFERT GALAXIES

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RESUMEN

Observaciones realizadas con el *HST* nos proveen con la resolución requerida para explorar en detalle las propiedades de la NLR (región emisora de líneas angostas) de las galaxias Seyfert. En galaxias Seyfert con emisión de radio extendida, las imágenes del *HST* muestran una correspondencia cercana entre la emisión de radio y de líneas ópticas. Interpretamos este resultado como evidencia fuerte de que el gas emisor de líneas está siendo comprimido por los choques resultantes del pasaje del flujo emisor de radio. El incremento de densidad producido por los choques hace que la emisión de líneas sea mucho mayor en la región donde esta interacción ocurre. Espectroscopía de la NLR confirma la presencia de una interacción fuerte: en la región de los radio jets, el campo de velocidad del gas está fuertemente perturbado, y muestra picos de emisión en dos velocidades separadas por hasta 1700 km s^{-1}. En varios puntos, las líneas de dos picos forman elipsoides de velocidad casi completos, indicando que vemos cáscaras de gas emisor en expansión. Concluimos que la morfología y cinemática de la NLR en estas fuentes está dominada por la presencia de los flujos emisores en radio, los cuales tambien podrían jugar un papel importante en el balance de ionización. Las observaciones de galaxias Seyfert son una herramienta única para el estudio de la energética y evolución de sistemas que muestran interacciones entre jets y el medio interestelar circundante.

ABSTRACT

HST observations provided us with the spatial resolution required to explore in detail the properties of the Narrow Line Region of Seyfert galaxies. In Seyferts with extended radio structures the *HST* images revealed a very close connection between radio and optical line emission. We interpret this result as strong evidence that the line-emitting gas is compressed by the shocks created by the passage of the radio-emitting outflow. The increase in the density due to the shocks causes the line emission to be highly enhanced in the region where this interaction occurs. Spectroscopy of the NLR confirms the presence of a strong interaction: in the region co-spatial with the radio-jets, the gas velocity field is highly perturbed and shows two velocity systems separated by as much as 1700 km s^{-1}. In several locations the split lines form an almost complete velocity ellipsoid, implying that we are seeing an expanding shell of gas. We conclude that the morphology and the kinematics of the NLR in these sources are dominated by the presence of radio outflows, which might also have a significant role in the ionization balance. Observations of Seyfert galaxies represent a unique tool to study energetics and evolution of ISM/jets systems.

Key Words: **GALAXIES: ISM — GALAXIES: JETS — GALAXIES: SEYFERT**

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1. INTRODUCTION

For many years it has generally been accepted that in the Narrow Line Region (NLR) of Seyfert galaxies the gas is photoionized by nuclear radiation (e.g., Ferland & Osterbrock 1986). Since in the framework of the unified model for Seyfert galaxies this radiation field is expected to be anisotropic (e.g., Antonucci 1993), the discovery of NLR with "cone-like" morphologies in initial *HST* observations of three nearby Seyfert galaxies (NGC 1068, Evans et al. 1991; NGC 4151, Evans et al. 1993, and NGC 5728, Wilson et al. 1993) seemed to give further weight to this longstanding view.

However, ground based studies have shown that the NLR is inevitably cospatial with the radio-emission (Wilson & Ulvestad 1983; Haniff, Wilson, & Ward 1988) and its kinematics clearly display signs of the effect of interactions with the ejected radio-plasma (Whittle et al. 1988; Baldwin, Wilson, & Whittle 1987; Pedlar et al. 1989). This association between the radio-emitting components and the NLR prompted Pedlar et al. (1989) and Taylor et al. (1992) to argue that the structure of the NLR is dominated by the compression and heating of the interstellar gas generated by shock waves formed by the supersonic radio-ejecta. The shock waves can

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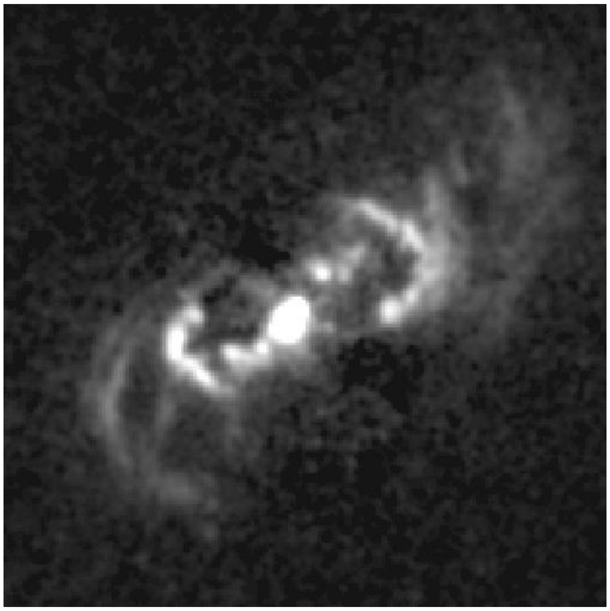

Fig. 1. Hα emission line image of Mrk 573 obtained with the WFPC2. The field of view for this image is $8.7'' \times 8.7''$.

be responsible for the ionization of the thermal gas and can also create significant continuum emission (e.g., Sutherland, Bicknell, & Dopita 1993) and this locally produced continuum can also be important in ionizing the NLR.

HST observations of the NLR of Seyfert galaxies provided us with the spatial resolution required to explore in detail the connection between the optical and the radio emission that, in these sources, extends over at most a few arcseconds.

2. MORPHOLOGY OF THE NARROW LINE REGION

HST imaging of Seyfert galaxies with extended radio sources has clearly shown that their NLR can not be simply described with a conical morphology. Two clear examples of this complex NLR structure are Mrk 573 and Mrk 3 (Capetti et al. 1996).

In Mrk 573, the large scale emission line structure is dominated by two spectacular narrow arcs located at $\sim 1.5''$ ($\sim$ 700 pc) from the nucleus (see Figure 1). Both arcs show significant corrugations and are broken into alternating dark and bright regions. They appear to be linked to the central region by two weaker S-shaped emission features, giving this complex the overall appearance of a double bubble. Fainter and more diffuse arcs are seen at larger radii on both sides of the NLR at a distance as large as $4''$ ($\sim$ 2 kpc) from the nucleus and cover approximately the same range in position angles as the inner arcs.

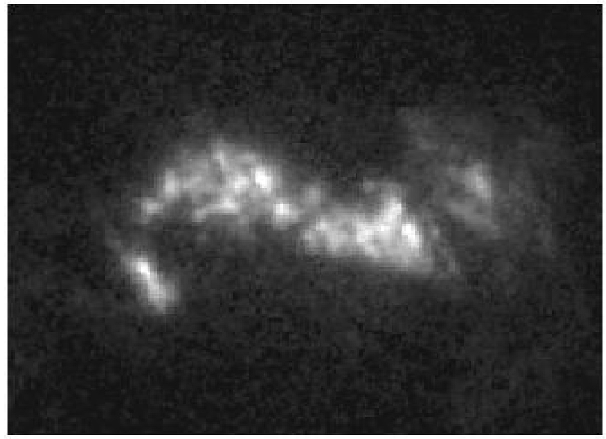

Fig. 2. [O III] emission line images of Mrk 3. The field-of-view is $3.0'' \times 2.2''$.

In Mrk 3 the overall appearance of the NLR is that of a bright S-shaped emission line region which extends over more than $2''$ ($\sim$ 800 pc). The S-shaped structure is composed by a large number of discrete knots superimposed on an emission background, which forms a lower luminosity halo of diffuse emission (see Figure 2).

3. THE CONNECTION BETWEEN RADIO AND OPTICAL NLR STRUCTURE

The complex NLR morphologies observed are readily explained once they are compared to their radio structure. For example, in the case of Mrk 573, the two main arc-like structures surround the two opposite radio-lobes seen in the VLA image (Wilson & Ulvestad 1983); in Mrk 3 the quasi-linear NLR is essentially co-spatial with the highly collimated pair of radio-jets (Kukula et al. 1993) of this galaxy.

We report here two further examples of association between radio-ejecta and emission line gas, Mrk 348 and NGC 1068.

In Mrk 348, the radio image (Neff & De Bruyn 1983) shows a quasi-linear structure, dominated by three compact components, $0\farcs25$ in size. The central component is probably the radio-core, having an inverted radio spectrum (Unger et al. 1986). The line emission is closely cospatial to the radio structure (see Figure refmrk348radio) being confined to a similarly linear structure, $0\farcs45$ in size and oriented along the same position angle of the radio axis.

In the NLR of NGC 1068 a strong anti-correlation between radio and optical emission is revealed (see Figure 4): the radio-jet lies on a region of relatively low optical emission and is surrounded by line emitting clouds. On a larger scale, the radio emission of NGC 1068 is dominated by two radio lobes that extend over $\sim 15''$(Wilson & Ulvestad 1983). Also

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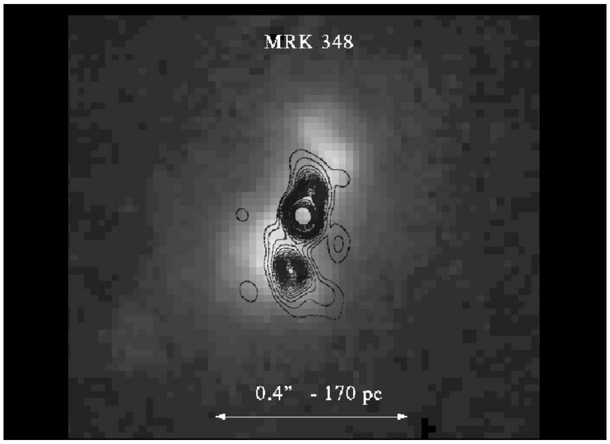

Fig. 3. [O III] emission line image of Mrk 348 with a field of view of 1″ × 1″ with superimposed radio contours from the 5 GHz MERLIN radio contour image of Pedlar & De Bruyn (1983).

on this scale, there is a strong radio/optical correspondence (Capetti, Axon, & Macchetto 1997): an emission-line filamentary system enshrouds the North radio-lobe and its sharp outer edges are bracketed by the two brightest emission filaments. Outside the radio lobe the emission-line surface brightness drops dramatically.

The close association between the NLR emission line morphology and that of the radio-emission is observed in essentially all Seyfert galaxies with an extended radio-source (see, e.g., Bower et al. 1995; Capetti et al. 1995; Falcke et al. 1996; Simpson et al. 1997; Falcke, Wilson, & Simpson 1998; Ferruit et al. 1999; Cooke et al. 2000).

Furthermore, it appears that the NLR takes a different form depending on the structure of the radio-emission. Emission line regions associated with radio-lobes are shell-like or bow-shock like while those associated with the jets are linear. We interpret these results as strong evidence that the line-emitting gas is compressed by the shocks created by the passage of the radio-emitting outflow. The increase in the density due to the shocks causes the line-emission to be highly enhanced in the region where this interaction occurs. The shell-like morphology of the emission line gas associated with the radio lobes is formed by the sweeping-up of material by the ejected and expanding lobes, while the linear structure associated with the jets arise due to the lateral expansion of hot gas around the jet axis.

The observations of NGC 1068, thanks to the smaller linear scale accessible, have revealed finer details of the interaction between the thermal and relativistic components. In particular the anti-

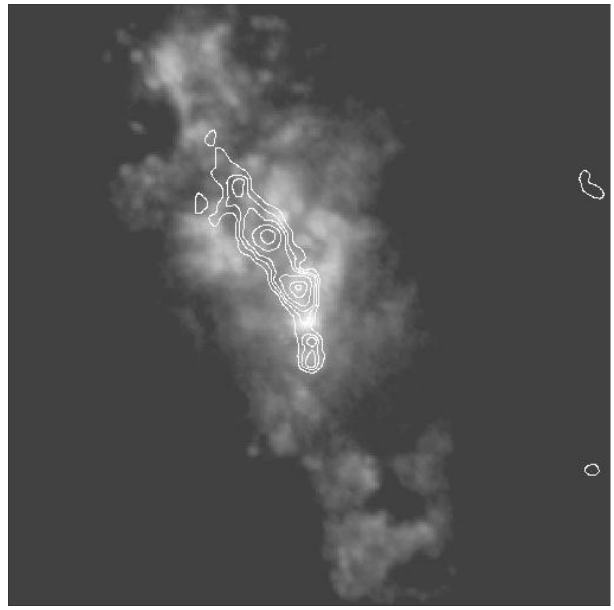

Fig. 4. Contours of the 6 cm MERLIN radio image of Muxlow et al. (1996) overlaid onto the [O III] emission line image from Macchetto et al. (1994). Note the anti-correlation between radio and line emission. The field of view is 4″× 4″, approximately 300 × 300 pc.

correlation between radio and optical emission is due the outflowing jet that is clearing a channel in the interstellar medium. This channel can be resolved in its transverse direction, showing its central gas-depleted core and the compressed gas clouds along the edges of the radio jet producing the emission line knots.

4. KINEMATICS OF THE NLR GAS

If the NLR morphology is indeed dominated by the interaction between the radio outflows and the external medium, we expect to find a similarly strong kinematical signature in the NLR velocity field. We have then obtained *HST* FOC f/48 long–slit spectroscopy of the Narrow Line Region of two Seyfert 2 galaxies, NGC 1068 and Mrk 3 with a spectral resolution of 1.78 Å/pixel. At a spatial scale of 0.″0287 per pixel these data provide an order of magnitude improvement in resolution over ground based spectra. Spectra were taken at several NLR locations, with the slit (0.″063 × 13.″5 in size) always oriented to be, as close as possible, perpendicular to the radio axis. This observational setting will allow us to trace in detail the interaction between the radio jet and the external gas.

4.1. *NGC 1068*

For the observations of NGC 1068, the slit was placed at a position angle of 83° and spectra were

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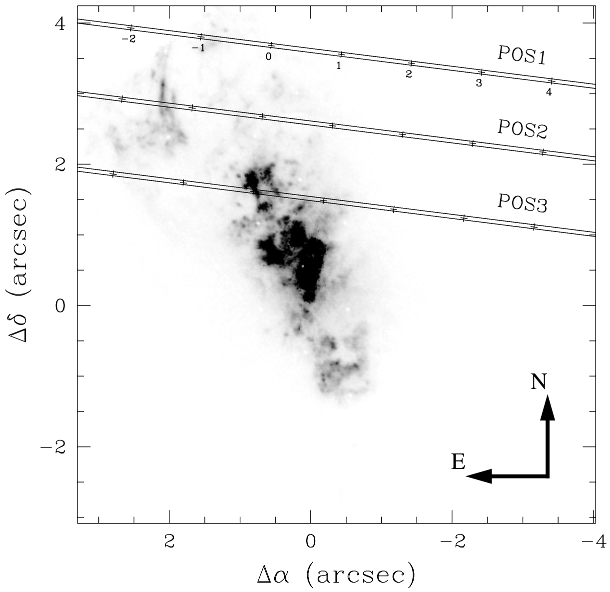

Fig. 5. The slit positions used in our study overlayed on a gray scale map of the [O III] image of Macchetto et al. 1994. The origin of the spatial axis on the borders of the image is centered on the position of the hidden nucleus (Capetti et al. 1995).

taken at 6 locations separated by 1″. Unfortunately, due to a guide star re-acquisition failure, only 3 of the slit locations (all North of the galaxy nucleus, see Figure 5) yielded usable spectra which we identify as POS1, POS2 and POS3 respectively.

At the slit location closest to the nucleus (POS 3), we observed that, within a distance of ±0.″7 from the radio-jet axis, the emission lines are kinematically disturbed and split into two components whose velocity separation is 1500 km s^{-1} (see Figure 6). The filaments associated with the radio lobe also show a strong redshifted kinematic disturbance of the order of 600 km s^{-1}, which probably is a consequence of the expansion of the radio plasma.

Furthermore, the material enveloping the radio-jet is in a much higher ionization state than that of the surrounding NLR gas. The highest excitation is coincident with the jet axis where emission in the coronal line of [Fe VII] λ3769 Å is detected and the [He II]λ 4686 Å is strong but where [O II] λ3727 Å is depressed. This large localized increase in ionization on the jet axis is accompanied by the presence of an excess continuum. Because the electron density is substantially larger in the jet compared to the surrounding NLR (see Capetti et al. 1997), these results can only be explained if there is a more intense ionizing continuum associated with the jet. This can be accomplished in a variety of ways which include an intrinsically anisotropic nuclear radiation field, a reduced gas covering factor or the presence of a local ionization source.

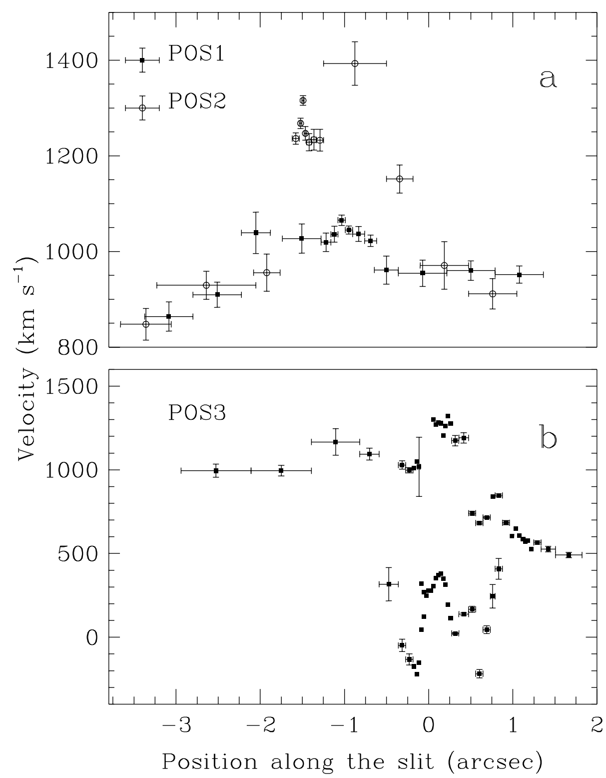

Fig. 6. Velocity fields measured at the three slit positions. Lower panel: Around the jet axis, at POS3, the gas is strongly kinematically perturbed and shows split lines with components separated by ∼ 1500 km s^{-1}. The dashed lines mark the systemic velocity of NGC 1068 (Baan & Haschick 1983). Upper panel: at POS2 and POS1 there are also large velocity perturbations at the location of the emission line filaments.

4.2. *Mrk 3*

Mrk 3 spectra were obtained at six locations across its NLR (Capetti et al. 1999) and with the slit oriented at a position angle of −25°, again almost perpendicular to the radio axis (see Figure 7).

In the region cospatial with the radio-jet, where the brightest emission line knots are located, the velocity field is highly perturbed and shows two velocity systems separated by as much as 1700 km s^{-1}(see Figure 8). In several locations the split lines form almost complete velocity ellipsoids implying that we are seeing an expanding shell of gas. We interpret this to be the consequence of the rapid expansion of a cocoon of hot gas, shocked and heated by the radio-emitting outflow, which compresses and accelerates the ambient gas. Particularly interesting is the comparison of the velocity field at slit locations which do

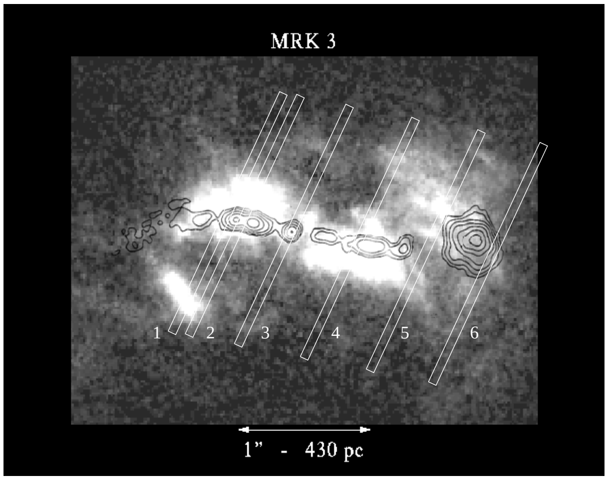

Fig. 7. *HST*/FOC image of Mrk 3 in the [O III] emission line from Capetti et al. (1996) with the contour radio image from Kukula et al. (1993) superimposed and the 6 slit positions where the spectra were taken.

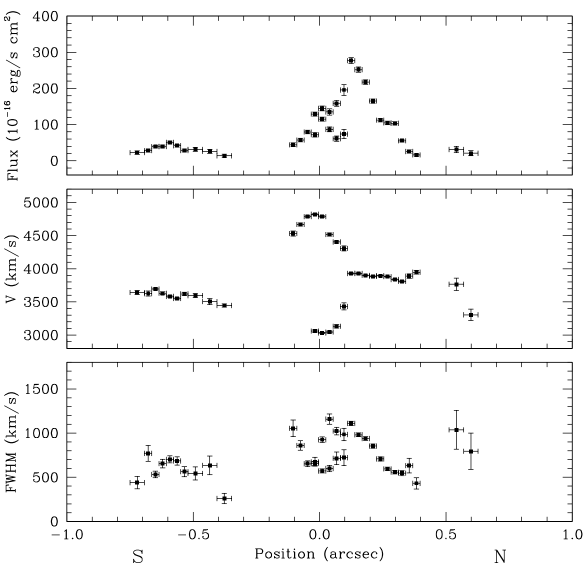

Fig. 8. Intensity (upper panel), velocity (middle panel) and line widths (lower panel) measured at the slit position POS3.

not cross the radio jet (see Figure 9) such as POS 6: here we only see quiescent ambient gas, with a velocity amplitude of less than 100 km s^{-1} which appears to be simply dominated by a disk rotation.

The gas motions within the NLR of Mrk 3 are therefore clearly dominated by the interaction between the jets and the interstellar medium and the NLR itself is essentially a cylindrical shell expanding supersonically.

The diameter of this shell ($\sim$ 200 pc) is much larger than the width of the radio-jet ($d < 15$ pc). This is an indication that the radio-plasma does not

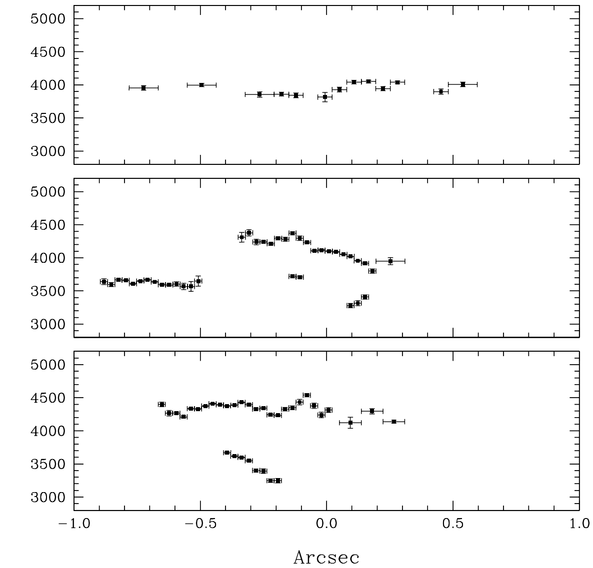

Fig. 9. Comparison of the velocity field at three positions across the Mrk 3 NLR. The upper panel (corresponding to POS 6) represents a slit location that does not intersect the radio jet and where we only see the unperturbed ambient gas with a quiescent a velocity field.

interact *directly* with the line emitting gas. This is physically expected since for a shock velocity of $\gtrsim$ 1000 km s^{-1} the post shock temperature will be of $\gtrsim 10^7$ K (Taylor et al. 1992). A hot high-pressure cocoon then develops around the advancing radio-jet and mediates the energy exchange between jets and line emitting gas.

With its current size of 200 pc the cocoon has expanded to several disk scale heights. Due to the external gas density stratification, the hot gas located above the plane of the disk blows out into the halo, puncturing the bubble and fracturing the velocity ellipsoids. The system is now effectively momentum driven.

From the size and velocity of the expanding region, we derive an upper limit to the radio-source age, $\lesssim 1.5 \times 10^5$ years, and a lower limit for the jet power, $\gtrsim 2 \times 10^{42}$ erg s^{-1}, required to inflate the cocoon. The total kinetic energy of the high velocity gas associated with the radio-jet can be estimated as $\sim 6 \times 10^{54}$ erg, which is comparable to the total energy carried by the jet over its lifetime. This quantitatively supports the idea that indeed the NLR gas is accelerated by the jet.

As radio-outflows are associated with a large fraction of Seyferts galaxies with typical sizes always smaller than a few kpc, if the advance speed and age of Mrk 3 are representative of the Seyfert pop-

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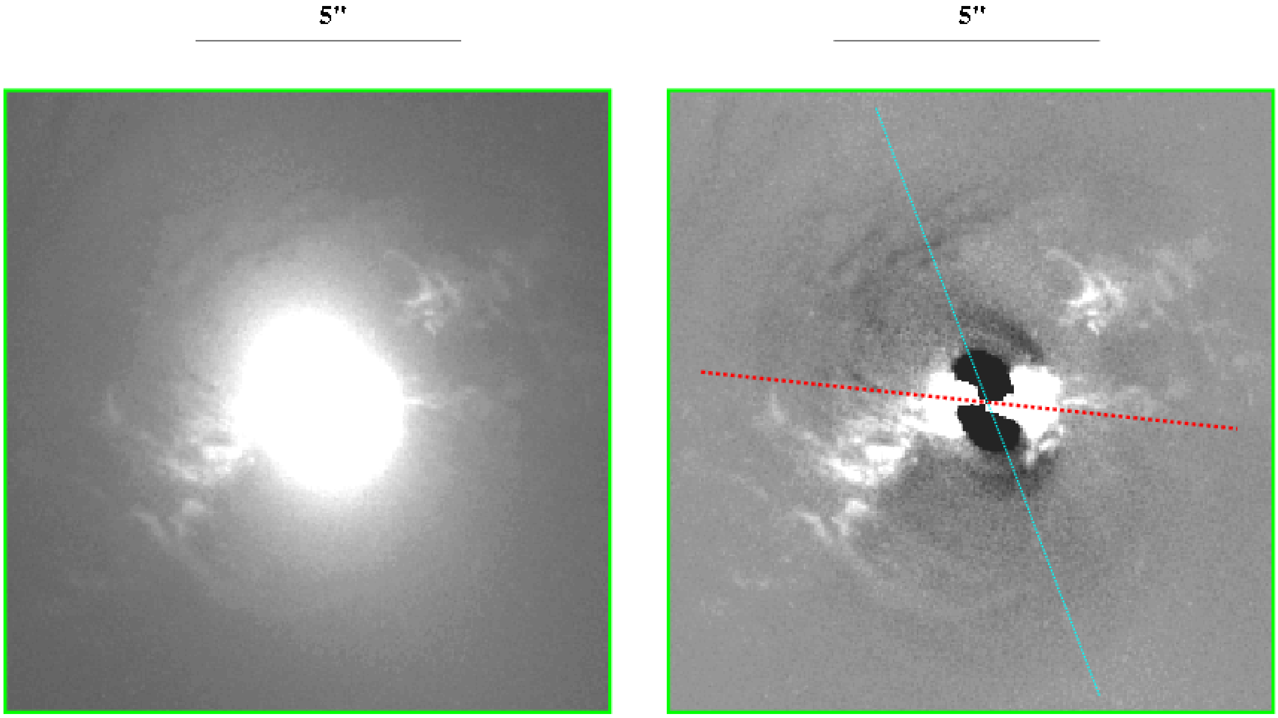

Fig. 10. Left panel: broad band F606W image of Mrk 3 including the Hα and [N II] emission line; right panel: same image after subtraction of an elliptical model for the galaxy starlight. The dotted black line marks the radio axis while the solid white line indicates the galaxy major axis.

ulation then these sources must also be short lived and probably recurrent.

5. ON THE ORIGIN OF THE EXTENDED EMISSION LINE REGIONS

In several Seyfert galaxies the emission line region extends well beyond the size of the radio emission. This gas usually shows a quiescent velocity field consistent with being simply ambient gas that is taking part in the galactic rotation and that is illuminated by the (anisotropic) nuclear radiation field (e.g., Unger et al. 1987; 1992).

However, the *HST* images show several cases in which the morphology of the ENLR is rather complex, such as in Mrk 573 and NGC 3393 (Capetti et al. 1996; Cooke et al. 2000). Their ENLR take the form of two diffuse arc-like structures reminiscent of those seen at smaller radii surrounding their radio lobes, placed symmetrically with respect to the nucleus and which cover approximately the same range in position angles as the inner arcs. As we have seen that radio sources associated with Seyfert galaxies might be recurrent, they might represent relics of previous events of nuclear activity. The current expansion of the radio lobes must occur at sufficiently low velocity that it does not produce significant perturbation of the gas velocity field.

A different and rather spectacular example comes from Mrk 3. In ground based images its ENLR has an approximately conical shape (Pogge & De Robertis 1993). However, *HST* images (see Figure 10) reveal that this structure is formed by two filamentary systems, extending symmetrically from the nucleus, which are continuously connected to the central NLR regions. As discussed above, the cocoon formed by the Mrk 3 jet has expanded to several disk scale heights and the hot gas located above the plane of the disk blows out into the halo. In this situation, the gas will follow the direction of higher external pressure gradient and it is expected to expand preferentially along the galaxy minor axis as indeed observed. We then suggest that the ENLR of Mrk 3 represents the warm phase of a large scale hot outflow driven by the energy deposited by the jet in the inner cocoon.

These results indicate that radio-outflows can affect the properties of the gas in Seyfert galaxies well beyond the current size of their radio sources.

6. SUMMARY AND CONCLUSIONS

HST observations have shown that in essentially all Seyfert galaxies harboring a radio source sufficiently extended to be well resolved at the *HST* resolution, the morphology of the Narrow Line Region

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is closely correlated with that of the radio emission. Furthermore, it appears that the NLR takes a different form depending on the radio structure: emission line regions associated with radio-lobes are shell-like or bow-shock like while those associated with the jets are linear. Long slit spectroscopy observations confirm this scenario, showing the clear kinematical signature in the NLR velocity field due to the acceleration of the ambient gas induced by the expanding radio plasma.

In general *HST* observations of Seyfert galaxies were biased towards objects of higher line luminosity that, due to the well known correlation between radio and line luminosity present in Seyfert galaxies, are also the brightest radio sources. This casts some doubt on the importance of the jet/cloud interaction in the Seyfert population as a whole. Nonetheless, extended radio sources are present in a very high fraction of Seyfert galaxies (from 50 to 90 % depending on the sample studied and on the quality and frequencies of the radio maps, e.g., Ulvestad & Wilson 1989; Kukula et al. 1995; Nagar et al. 1999; Thean et al. 2000) indicating that nuclear outflows are a general characteristic of these sources. Furthermore, *HST* observations of a complete sample of early type Seyfert galaxies (Ferruit et al. 1999) confirmed the general trend of a close radio/optical association. In particular, in several objects in which the radio source is unresolved, the *HST* images showed an equally compact emission line region. This clearly suggests that jet/cloud interaction occurs also in these objects, although on a scale which cannot currently be resolved with optical telescopes. Observing the brightest radio objects caused the selection of the most extreme examples of a physical phenomenon that appears to be common to all Seyferts.

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