Dust lanes causing structure in the extended narrow line region of early-type Seyfert galaxies

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ABSTRACT

We construct near-infrared to visible broad band NICMOS/WFPC color maps for 4 early-type Seyfert galaxies with S-shaped or one-sided ionization cones. We find that dust lanes are near or connected to many of the features seen in the [OIII] and Hα+[NII] line emission maps. This suggests that much of the structure of line emission in these ionization cones is determined by the distribution of ambient dense galactic gas. Spiral arms, dust lanes caused by bars, or gaseous warps provide dense gas which when illuminated by a conical beam of ultraviolet photons can result in the complicated line emission morphologies observed.

Subject headings: galaxies: active — galaxies: ISM — galaxies: Seyfert — galaxies: structure

1. Introduction

In Seyfert galaxies when radiation is obscured by an inner optically thick 'torus' (Antonucci 1993) ultraviolet (UV) radiation can escape along a conical shaped beam causing an "ionization cone" to be observed in emission line maps (e.g., Evans et al. 1991, Pogge 1989). The observed morphology and luminosity of the ionization cone can be influenced by the density distribution of the ambient media (e.g., as simulated by Mulchaey, Wilson & Tsvetanov 1996). For example, in NGC 4151 extended gas is produced by the intersection of the ionization cone with the disk of the galaxy (Pedlar et al. 1993; Boksenberg et al. 1995; Wilson & Tsvetanov 1994). In samples of Seyfert galaxies the orientation of [OIII] and Hα+[NII] line emission is generally near that of the galaxy major axis (Nagar et al. 1999, Mulchaey & Wilson 1995). This suggests that the availability and distribution of dense galactic gas plays an important role in determining the width and orientation of the ionization cone.

Extended emission-line and radio morphologies are often co-spatial or aligned in Seyfert galaxies (e.g., Unger et al. 1987; Pogge 1988). This supports the idea that ionizing photons

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preferentially escape along the radio axis. The connection between the radio ejecta of Seyfert nuclei and their extended emission line regions is evident from the similar spatial extents observed in high angular resolution radio interferometric observations compared to Hubble Space Telescope (HST) images (e.g., recently Simpson et al. 1997; Falcke, Wilson & Simpson 1998; Mulchaey et al. 1994; Ferruit, Wilson & Mulchaey 1998). However, the morphologies observed in lines from ionized gas [OIII]5007$\mathring{A}$ and Hα+[NII]$6548, 6583\mathring{A}$ can be complex, showing S-shaped features, partial loops, and curves suggestive of bow shocks. Except for observations showing that high excitation gas tends to form a cone shaped morphology, no pattern has emerged connecting the complicated morphologies observed in the ionized gas distribution among different Seyfert galaxies. In particular it not clear what role the distribution of ambient galactic gas plays compared to energetic hydrodynamical processes caused by the jet.

In this paper we take the opportunity provided by high angular resolution near-infrared imaging with NICMOS on HST to make color maps with previously observed visible wavelength HST/WFPC2 images. We find that the resulting color maps show extinction from dust features with higher signal to noise than possible with color maps made previously from the existing WFPC2 images alone. This could be because the large wavelength separation between the visible and near-infrared images makes it easier to identify features with low column depths of dust. We present here a comparison between morphology observed in these color maps (tracing dust features) and that displayed in [OIII] and Hα+[NII] line emission from ionized gas. Using these color maps we can examine how the distribution of ambient dense gas in the galaxy affects the morphology of the line emission.

We chose Seyfert galaxies with existing high quality images observed with WFPC or WFPC2 and NICMOS and published recent literature discussing their ionization cone morphology. Galaxies were also chosen to be early-type galaxies so as to minimize confusion caused by star formation and by extreme extinction from dust. This limited our sample to 4 galaxies: Markarian 573, NGC 3615, NGC 2110 and NGC 5643. All are Seyfert 2 galaxies except for NGC 3615 which is a Seyfert 1. The Hubble types range from SB0 to SAB.

A number of dynamical models or scenarios have been proposed to explain the individual galaxy morphologies. In NGC 3615 a bent bipolar mass outflow model was suggested (Goad & Gallagher 1987; Mulchaey et al. 1992) to account for the S-shape of the ionized gas. Alternatively a precessing jet model might also be appropriate (Veilleux, Tully, & Bland-Hawthorn 1993). In Markarian 573 inner knots nearest the radio jet may represent deflection of the jet by ambient or entrained clouds, whereas the inner arcs at $1''.8$ may represent bow shocks driven by the jets (Ferruit et al. 1999). Despite the similarity between the inner and outer arcs at $3''.6$ this mechanism is unlikely to apply to the outer arcs. In NGC 2110 a pair of curved features of ionized gas is observed which are offset from the radio jet itself (Mulchaey et al. 1994). This might be consistent with a model where gas is swept up or ejected by the jet, but the relative positions of the radio emission and the emission line features remains difficult to explain (Mulchaey et al. 1994). Despite the similarity between the inner and outer emission features in NGC 2110 the outer S-shaped region of ionized gas at $4''$ from the nucleus is suspected to be caused by a different mechanism, that of ambient interstellar gas photoionized by the central source (Mulchaey et al. 1994). Many of these studies and interpretations were hampered by the lack of information about the distribution of ambient galactic material. In this paper we search for a simple explanation for the variety of emission line morphologies observed in these galaxies.

2. Comparison of near-infrared/visible color maps with emission line maps

WFPC, WFPC2 (visible) and NICMOS (near-infrared) images were taken from the HST archive. For more information on the visible band images see the original papers discussing the HST observations (on NGC 3516; Ferruit et al. 1998, on NGC 5643, Simpson et al. 1997, on NGC 2110; Mulchaey et al. 1994, on Markarian 573; Ferruit et al. 1999, Falcke et al. 1998). NICMOS Camera 2 images in the filter F160W (centered at 1.60μm) were primarily from the snap shot program 7330 (Regan & Mulchaey). For NGC 2110 we used the narrow band image in the filter F200N (centered at 2.00μm) from GO program 7869. The NICMOS images were reduced with nicred (McLeod 1997) with on-orbit flats and darks. In Figures 1-4 we show ionized gas traced in either [OIII] or in Hα+[NII] for the four galaxies. We also show color maps constructed from NICMOS and WFPC2 images.

2.1. NGC 5643

The isophotes in the outer parts of the NICMOS camera 2 F160W, 1.6μm image are roughly aligned with a large scale bar (with major axis $PA \sim 90°$, and extending to a radius of $r_b \sim 30''$, Mulchaey, Regan & Kundu 1997). No inner bar is detected in this image. The color map shows a pair of extinction features consistent with leading dust lanes along but offset from the major axis of the bar. Knots observed in [OIII] are probably not directly associated with any dust features observed in the galaxy. However, the southern side of the ionization cone displays a component of diffuse emission which appears to be bounded by the dustlane seen on the south east side of the galaxy. The dust lane appears to be very slightly offset to the south from the diffuse component of the line emission. This could be explained by a projection effect if the UV radiation beam from the central source (or from shocks caused by the jet, e.g., Dopita & Sutherland 1995) illuminates material somewhat above but not in the plane of the galaxy. This offset could also be explained by a model where dense material originally from the dust lane is entrained by moving material associated with the jet ($PA \sim 90°$, Morris et al. 1985).

2.2. NGC 2110

For NGC 2110 the deepest visible broad band image available was the F606W broad band filter which is somewhat contaminated by line emission. However the extent of dust lanes can be seen outside the ionization cone and includes large areas which are not confused by the line emission. The overall pattern is that of spiral dust lanes which could be part of spiral arms. In particular dust features are observed at about $4''$ and $8''$ north of the nucleus, roughly corresponding to the two arcs seen in the Hα and [OIII] emission maps (Mulchaey et al. 1994). A dust lane is also observed to the south of the nucleus corresponding to a broad curve of line emission about $2''$ south of the nucleus. The dust features appear to be offset from the line emission, being slightly more distant from the nucleus than the line emission (see the above discussion on NGC 5643 relating to this).

2.3. NGC 3516

On large scales NGC 3516 is barred with major axis $PA \sim 170°$ and extending to a radius of $r_b \sim 13''$ (Mulchaey et al. 1997). In the F160W image the isophotes are slightly elongated in a direction roughly perpendicular to this outer bar (at $r \sim 3''$) and so the galaxy may be doubly barred. However the morphology of the dust features observed in extinction in the color map and gas kinematics are not consistent with what would be expected from gas in the plane of the galaxy (see discussion in Ferruit et al. 1998, Veilleux, Tully, & Bland-Hawthorn 1993). When gas exists above the plane of galaxy a warped configuration is most likely (e.g., Tubbs 1980). To the south of the nucleus a curved dust feature is observed in the color map. The shape of this dust feature corresponds quite well with the morphology of the [OIII] emission and suggests that dust is associated with the ionized gas. To the north west and south east of the nucleus extinction features are observed which are not co-spatial with bright line emission. We note that the F547M image we used to make the color map should be free of line emission.

2.4. Markarian 573

On large scales Markarian 573 is barred with major axis $PA \sim 0°$ and extending to a radius of $r_b \sim 10''$ (e.g., Alonso-Herrero et al. 1998). In the F160W image there is a strong elongation almost exactly perpendicular to the larger scale bar at $r \sim 2''$ which corresponds to an inner bar (noted by Pogge & DeRobertis 1993). There is also a pair of dust lanes slightly offset from the major axis of this inner bar (Pogge & DeRobertis 1993) which would be consistent with leading dust lanes along this bar, however a warped dusty disk oriented perpendicular to the jet might also be present.

Unfortunately the F606W filter is strongly contaminated by line emission. However, in the

F606W/F160W color map we can trace the extent of dust features outside the ionized gas. To the east of the nucleus 2 linear dust features are connected to the 2 south eastern arcs of line emission suggesting that they are likely to continue within the region of line emission. To the south there is also a dustlane which connects to the outer arc. The morphology of the line emission and dust lanes is reminiscent of double spiral arms which are sometimes observed at the ends of a bar (e.g., in NGC 1365, Lindblad, Lindblad, & Athanassoula 1996). The linear feature of high excitation emission within an arcsec from the nucleus does not correspond to any dust features and so is probably directly associated with the jet (as discussed in Ferruit et al. 1999, Falcke et al. 1998).

2.5. Interpretation

Spiral arms and bars can cause gas mass surface density contrast ratios (between arm and inter-arm of dustlane and inter-dustlane) of greater than a factor of few in the plane of the galaxy (e.g., Hausman & Roberts 1984, Athanassoula 1992). Extinctions measured from our color maps are similar to that estimated from visible color maps and range from $A_V \sim 0.5 - 1.5$ mag in the dust features (e.g., Simpson et al. 1997, Mulchaey et al. 1994, Ferruit et al. 1998) corresponding to $N_H \sim 3 - 9 \times 10^{21}\mathrm{cm}^{-2}$ using a standard ratio of total hydrogen column depth to color excess. Outside the dust features visible to infrared colors match those on the opposite side of the galaxy nucleus allowing us to limit $A_V \lesssim 0.1$ mag inter-arm (or inter-dustlane). This implies that the minimum surface density contrast ratio between arm/inter-arm (or dustlane and inter-dustlane) is a factor of a few. The dust features that are evident in our visible/infrared color maps therefore represent a significant source of dense galactic gas compared to that outside these features.

Densities estimated from emission line diagnostics are relatively high (~ 30 cm^{-3} for NGC 3516, Ulrich & Péquignot 1980; $100 - 850$ cm^{-3} depending on the arc in Markarian 573, Ferruit et al. 1998; ~ 50 cm^{-3} in a particular knot in NGC 5643, Simpson et al. 1997). Using these densities to estimate the total number of ionized hydrogen from the Hα line strength we estimate that $N_{H,ion} \sim$ a few $\times 10^{21}$ cm^{-2} in Markarian 537, NGC 2110 and NGC 3516 and a factor of 10 lower in NGC 5643. We estimate that these column depths are a significant fraction of those estimated above from the color excesses or extinctions in the dust features. The high densities and large column depths of ionized hydrogen suggest that a nearby source of dense galactic gas is required to account for their existence. The dust lanes provide a nearby source of dense gas which does not exist outside these regions.

The emission measure of an emission line is proportional to the density squared and so is a strong function of the gas density. This implies that denser material should produce brighter line emission. If UV photons preferentially escape along a conical radiation beam, the densest material illuminated by this beam would be easiest to see in a line emission map. Alternatively in models where the interaction of the radio eject and the ambient medium could also produce ionizing radiation (e.g., Dopita & Sutherland 1995) we would also expect a bias towards detecting denser gas associated with dust features. When dense gas exists in the plane of the galaxy we preferentially expect to see line emission near this plane, and associated with denser media which would be traced by dust lanes.

3. Discussion

For 4 early-type Seyfert galaxies we demonstrate that dust lanes are near features seen in line emission maps in the extended emission line region. In NGC 5643 a component of diffuse line emission is bounded by a dustlane on the south eastern side of the ionization cone. In NGC 2110 3 spiral dust lanes have similar curvature and location to 3 arcs seen in line emission maps. In Markarian 573 on the east side 2 linear dust lanes merge into the two south eastern line emission arcs. To the south a linear dustlane merges into the south eastern outer arc. In NGC 3615 to the south west of the nucleus patchy dust features exist near the location of bright line emission. The dust features continue outside the region of ionized emission to the north west and south east of the nucleus.

The proximity of dust features with line emission suggests that the morphology of the line emission is affected by spiral arms or bars (except for NGC 3615 where the dust may be part of a gas warp). Dense gas in these dust features is more likely to result in bright line emission when illuminated by a UV source or when affected by a jet.

When spiral arms or bars are present, moderate deviations from circular motion caused by streaming are expected. This could explain some (but not all) of the peculiarities observed in the velocity fields (e.g., in Markarian 573; Ferruit et al. 1999). However, we note that not all of the line emission features are associated with dust lanes. This is illustrated with Markarian 573 and NGC 5643 where many of the features observed in the [OIII] emission map do not have nearby dust lanes. We would expect that galaxies with a larger fraction of active star formation than the galaxies presented here may have much more complicated ionized gas structure because of their multiple sources of UV radiation (e.g., as seen in Circinus, Maiolino et al. 1999). The galaxies studied here have ionization cones which extend hundreds of pc from the galaxy nucleus, and well outside a gas disk exponential scale length. Ionization cones on small scales within a gas exponential length would not be expected to be so sensitive to the distribution of galactic gas in the plane of the galaxy.

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Table 1. Images

Galaxy (1)	Scale 1″ (2) (pc)	Line Filter (3)	Continuum Filter (4)	Visible Filter (5)	Near-IR Filter (6)	Max Contour (7) (mag/″^{2})
NGC 5643	77	F502N	F547M	F814W	F160W	10.5
NGC 2110	148	F664N	F718M	F606W	F200N	11.0
NGC 3516	171	FR533N	F547M	F547M	F160W	13.0
MRK 573	335	FR533N		F606W, F675W	F160W	12.0

Columns– (1) Galaxy; (2) Scale in pc for 1″ assuming $H_0 = 75$km s^{-1} Mpc^{-1}; (3) The [OIII] or Hα+[NII] emission map was constructed using this filter containing the emission line; (4) The line emission map was constructed using this continuum filter. Line and continuum images were all observed with WFPC2 except in the case of NGC 2110 which was observed with the planetary camera; (5) The WFPC2 image we used to construct color maps displayed in Figs. 1-4 was observed in this filter. Central wavelengths are F547M (0.547μm), F606W (0.60μm) and F675W (0.675μm); (6) The NICMOS filter in which the near-infrared image was observed that we used to construct color maps and display contours shown in Figs. 1-4, Central wavelengths are F160W (1.60μm) and F200N (2.00μm); All near-infrared images were taken on NICMOS/Camera 2 except for that of NGC 2110 which was taken with NICMOS/Camera 3; (7) Brightest F160W or F200N contour shown in Figs. 1-4. Calibration reference points were from M. Rieke private communication. The magnitudes in the F160W filter are very close to Johson H mags.