HUBBLE SPACE TELESCOPE OBSERVATIONS OF NGC 4151: IMPLICATIONS FOR THE UNIFIED MODEL OF AGN

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Abstract. *HST* Planetary Camera narrow band emission-line and continuum images are used to study the nuclear region of NGC 4151 at the highest possible spatial resolution. The [O III] λ5007 image reveals a striking biconical structure with a projected opening angle of $75° \pm 10°$, and whose apex coincides with the bright, unresolved central source. The projected axis is oriented along PA $60°/240° \pm 5°$, and is aligned with the extension of the nuclear VLBI radio source. Analysis of the geometry of the narrow-line region places our line of sight well outside the ionization cones, and yet we see nearly unobscured optical and near-UV continuum and broad lines. In addition, material with significantly different column densities is required to explain the numerous optical and UV absorption lines and the soft X-ray absorption. We conclude from these data that the simplest version of the obscuring torus unification model is inconsistent with the observations and some modifications are required. We discuss some alternative collimation mechanisms that are compatible with our observations.

1. HST Imaging Results

The nearby Seyfert 1.5 galaxy NGC 4151 has been a subject of numerous studies over the whole wavelength range. We have imaged the nucleus of NGC 4151 with the Planetary Camera onboard *HST* to study the morphology of the emission-line gas at the highest avilable today spatial resolution. Full description of our observations is given in Evans et al. (1993), and here we present the most important results and implications for the Unified Models of AGN.

On the *HST* imaging scale ($0\farcs1$ resolution) the nucleus of NGC 4151 is unresolved in both the continuum and emission-line images. A point-like nuclear source remains even after the continuum subtraction (see Fig. 1). The [O III] λ5007 emitting gas is distributed in a bi-conical structure with apices coincident with the nuclear point-like source with projected opening angle $\theta_{cone} = 75° \pm 10°$, and cone axis position angle $\mathrm{PA}_{cone} = 60°/240° \pm 5°$. The [O III] λ5007 emission is concentrated in filaments of discrete clouds with sizes of up to $\sim 0\farcs4$ ($\sim 20h$ pc; $H_0 = 100h^{-1}$ km s^{-1} Mpc^{-1}), implying that the clouds themselves are resolved.

On a larger (*arcsecond*) scale, the string-like Extended Narrow-Line Region (ENLR) inferred from the ground-based observations (e.g., Perez et al. 1989, Pérez-Fournon & Wilson 1990) is completely contained in the sector of the sky generated by extending the *HST* bi-conical structure to the radius of the ENLR. This suggests

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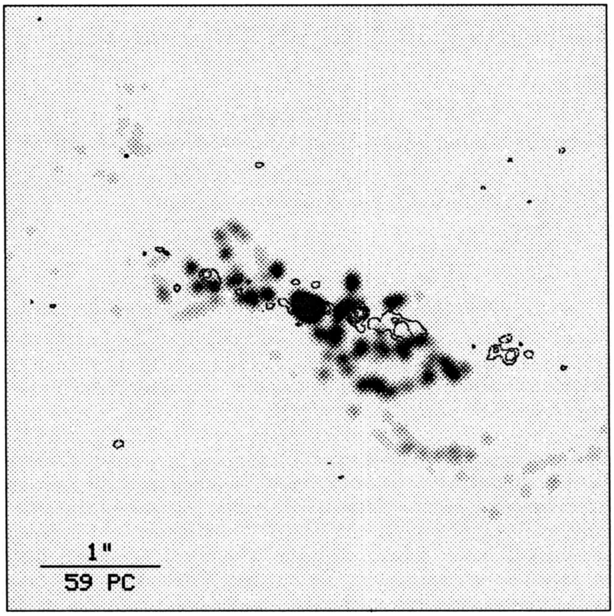

Fig. 1. MEM reconstruction of the continuum subtracted [O III] λ5007 image sampled at 4 times the original pixel sampling. The image is scaled as square root of the intensity between 0% and 15% of the peak value. Contours represent the 5 GHz MERLIN radio map from Pedlar et al. (1993) at 2.2,4.5,9,18,36,65 and 95% of the peak value. The suspected nuclear component of the radio image has been aligned with the position of the *HST* unresolved nuclear source.

very strongly that the extended emission-line gas is encapsulated *physically* within the volume of space subtended by the nuclear cones.

No line-emission is visible in our images in either [O III] λ5007 or Hα+[N II] in the direction perpendicular to the cones. The Hα+[N II] emission is due almost entirely to the unresolved nuclear point source, and there is additional weak Hα+[N II] emission associated with the extended bi-conical structure. This strongly implies that any theory aiming to explain the observed properties of NGC 4151 must incorporate a Broad-Line Region (BLR) not larger than few hundreds of an arcsecond on the sky.

Contrary to some other well studied cases (e.g., NGC 1068, Evans et al. 1991) there is little correspondence between the optical and radio emission on subarcsecond and arcsecond scales (see Fig. 1). The radio structure is misaligned by 12°–24° from our measured cone axis. The elongation of the nuclear VLBI radio source, however, is coincident with the symmetry axis of the [O III] λ5007 cones. This suggests strongly that a common mechanism may be responsible for the orientation of both the radio plasma and the ionizing radiation field.

2. Orientation and Geometry: Contradiction with the simplest Unified Model of AGN

From the ground, the string-like ENLR can be followed to more than $\sim 30''$ from the nucleus and is oriented along PA 228°(e.g. Schulz 1990). Based on the comparison of the H I velocities with the velocities of the ionized gas it has been shown that the string lies in the disk of the host galaxy and it is almost in the plane of the sky. The suggested inclination to our line of sight is $\sim$98°.

Previous ionization studies show that the gas in the ENLR is ionized by the nuclear radiation field as long as the string falls somewhere within the volume of the ionization cone. Kinematical studies of the gas in the ENLR imply that the SW cone is directed toward us and the NE cone is directed away from us. This orientation is also suggested by the fact that the filaments in the SW cone are generally brighter and more extended then their counterparts in the NE cone.

The geometry that minimizes the deviation between our line of sight and the nearest edge of the cone places the string along the far edge of the SW cone. With the above assumptions, and from the measured opening angle and orientation of the cones we derive a value of the true inclination of the cone axis to our l.o.s. $\phi \sim 65°$ and true cone opening angle of $\theta \sim 70°$. The inclination ϕ can be larger if the string falls totally within the cone instead of along the far edge. This implies that the *minimum* angle between our line of sight and the cone edge is $\sim$30°. We note here that the large inclination angle is in excellent agreement with the results of the optical and X-ray observations of NGC 4151.

The inferred geometry contradicts with the simplest version of the Unified Model in which an infinitely optically thick torus obscures the nucleus and collimates the ionizing radiation field. Since our line of sight is at least 30° off the edge of the cone, it must pass through the torus. It is also not possible to "see" the BLR over the edge of the torus because of the estimated sizes of both the BLR ($\sim$0.003 pc) and the continuum source ($\sim$0.0003 pc), and the expected distance of the inner wall of the torus to the continuum source ($\sim$0.2 pc).

Our line of sight to the central source and the BLR is not totally unobscured. The low energy turnover of the X-ray spectrum of NGC 4151 requires an absorbing column of $N_H(\text{X-ray}) \approx 10^{23}$ cm^{-2}, and the best model suggests partial covering of $\sim$90% of the source. Numerous absorption lines cover both the continuum and the broad emission lines (e.g. Kriss et al. 1992) at optical and UV wavelengths. These require a total equivalent hydrogen column density of $N_H(\text{UV}) \sim 10^{21}$ cm^{-2} and a neutral hydrogen column of $N_{H\,I} \sim 10^{18} - 10^{21}$ cm^{-2}.

It is clear from the geometry that an infinitely optically thick torus cannot collimate the ionizing radiation field, but the presence of a molecular torus cannot be ruled out. The larger cone opening angle we measure compared with the previous assumptions decreases the area of the sky subtended by the absorbing material by only $\sim$15%. This is not enough to significantly affect the overpredicted far IR luminosity. This controversy, however, is resolved in the recent theoretical studies which predict that the IR radiation from the torus is substantially anisotropic.

3. Collimating the Ionizing Radiation

In summary, our *HST* observations of NGC 4151 suggest that Unified Model must be made more complex to explain not only the collimation of the radiation into a bi-conical structure, but also to allow for a partially obscured view of the BLR and continuum source, and must explain the differing UV and X-ray column densities along our line of sight.

Consider a slight modification of the shadowing/obscuration scenario in which a physically thin, dense molecular torus is surrounded by a lower density atmosphere of neutral or semi-neutral gas. Hard X-ray heating or magnetically driven winds may "puff-up" the torus and lead naturally to such an atmosphere. The edges of the *ionization* cones will then be determined by the angle at which the path through the atmosphere gives a column density sufficient to block the ionizing ultraviolet. Columns of $N_H = 10^{20}$ cm^{-2} will be optically thick at all wavelengths past the Lyman edge up to the soft X-ray. Above the Lyman limit, and for normal gas-to-dust ratios, extinction will not have much impact up to column densities higher than several times 10^{21} cm^{-2}. Consequently, lines of sight outside the ionization cone but also outside the shadow of the opaque torus (the "twilight zone") will have a relatively clear view of the central regions at wavelengths longward of the Lyman edge. The atmosphere around the torus can explain the UV absorption lines, and higher density, fully ionized material inside the inner edge of the torus, e.g. in the BLR, may account for the higher X-ray column density.

The collimation of the ionizing radiation may not necessarily be related to the torus. A flattened configuration of optically thick broad-line clouds may produce the observed geometry. Such a distribution has been proposed to account for the X-ray observations, and by the reverberation mapping. And finally, the ionizing radiation may be intrinsically anisotropic, e.g. from a "naked" accretion disk around a supermassive black hole.

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