An HST/WFC3 mapping of optical emission lines from the nuclear spiral in M31

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Proprietary Period: 12

Orbit Request	Prime	Parallel
Cycle 18	8	8

Abstract

The nuclear spiral in M31, consisting of ionized and neutral dusty gas clouds of typically sub-parsec sizes, shows optical emission lines characteristic of LINERs. Yet the lack of UV radiation from either an active nucleus or massive young stars makes the ionizing source of this nearest LINER a longstanding puzzle. We propose a WFC/UVIS observation of the nuclear spiral, using appropriate narrow-band filters to map the H alpha, [N II] and [O III] lines. The resolving power of HST is essential to measuring the line intensities and their ratios from discrete gas clouds across the nuclear spiral, based on which we can derive the physical properties of gas such as density and ionization state. We will then assess the relative importance of ionization/excitation mechanisms, in particular UV radiation provided by evolved stars and heating by cosmic-rays, by confronting with theoretical models. This study advances our understanding of the regulation of galactic circumnuclear environments, which is in turn crucial to understanding the evolution of the central super-massive black hole and the host galaxy.

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Target Summary:

Target	RA	Dec	Magnitude
M-31	00 42 44.3100	+41 16 9.40	V = 3.44

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
M-31	WFC3/UVIS Imaging F373N		1
M-31	WFC3/UVIS Imaging F390M		1
M-31	WFC3/UVIS Imaging F502N		2
M-31	WFC3/UVIS Imaging F547M		1
M-31	WFC3/UVIS Imaging F656N		1
M-31	WFC3/UVIS Imaging F658N		1
M-31	WFC3/UVIS Imaging F665N		1
M-31	ACS/WFC Imaging F502N	CPAR	2
M-31	ACS/WFC Imaging F550M	CPAR	1
M-31	ACS/WFC Imaging F658N	CPAR	2
M-31	ACS/WFC Imaging F660N	CPAR	2
M-31	ACS/WFC Imaging F625W	CPAR	1

Total prime orbits: 8

Total coordinated parallel orbits: 8

■ Scientific Justification

1 Introduction and motivation

Understanding the regulation of galactic circumnuclear environments, in which the ISM and stars are densely co-spatial under extreme physical conditions, is essential to understanding the feeding and feedback of the central super-massive black hole (SMBH) and in turn the global evolution of the host galaxy. The Andromeda galaxy (M31) provides an ideal testbed for studying a galactic circumnuclear environment. Its proximity ($D \approx 780$ kpc; 1 arcsec = 3.8 pc) ensures observations with an unprecedented linear resolution for a massive external galaxy. Moreover, thanks to the low foreground and internal extinction ($A_V \lesssim 1$), the central region of M31 is transparent in the optical, ultraviolet and X-ray bands. This opens up the possibility of obtaining a comprehensive view to almost all phases of the ISM and various types of stars in the region (cf. Li, Wang & Wakker 2009 for an observational overview), which is inevitably hampered by the edge-on perspective to our Galactic center.

Indeed, optical observations have revealed remarkable features of circumnuclear ISM in M31. Through the spectroscopic detection of [O II], [O III], Hα, [N II] emission lines, the presence of circumnuclear warm, ionized gas has long been recognized (e.g., Rubin & Ford 1971). Narrow-band imaging observations (Jacoby, Ford & Ciardullo 1985; Boulesteix et al. 1987; Ciardullo et al. 1988; Devereux et al. 1994) further revealed that this gas is apparently located in a thin plane across the central few arcmins, showing filamentary and spiral-like patterns (see Fig. 1b). The integral of these features is referred to the *nuclear spiral*. In addition, optical extinction studies revealed the presence of interstellar dust (e.g., Sofue et al. 1994, Melchior et al. 2000), and hence presumably neutral gas, whose distribution markedly resembles that of the optical emission lines, i.e., the nuclear spiral. *Spitzer* observations now provide a definite view of the infrared (IR) emission from the nuclear spiral, once the underlying stellar IR emission is properly subtracted (Li et al. 2009).

The highly organized patterns in the nuclear spiral indicate a physical regulation. That the stellar disk of M31 is probably barred (Athanassoula & Beaton 2006) offers a viable formation mechanism for the nuclear spiral: an inflow of gas from the outer disk driven by bar-induced gravitational perturbations (e.g., Stark & Binney 1994; Maciejewski 2004; see Fig. 1a). It is expected that a passive accumulation of circumnuclear ISM eventually leads to nuclear (i.e., accretion-powered) and/or star-forming activities, but neither kind is observed in M31. A plausible interpretation, proposed by Li et al. (2009), is that a corona of hot (a few 10^6 K) gas, filling the circumnuclear volume and forming a bulge outflow, evaporates the nuclear spiral. Evidence for such an outflow is recently found by sensitive *Chandra* X-ray observations (Li & Wang 2007; see Fig. 1). Inherent regulations such as thermal conduction among the multi-phase ISM is likely a generic character of galactic circumnuclear environments. The nuclear spiral in M31 affords us a great opportunity to study the relevant physical processes.

Were M31 a member of the Virgo cluster (i.e., the linear scale is smeared by a factor of 20), the nuclear spiral would have been simply classified into a low-ionization nuclear emission-line region (LINER). In fact, the nuclear spiral exhibits an integrated Hα+[N II] luminosity of $\sim 10^{39}$ ergs s^{-1} and an averaged [N II]λ6583/Hα intensity ratio of $\sim$2 (Ciardullo et al. 1988), both values typical of LINERs, e.g., observed in the Palomar spectroscopic survey (Ho, Filippenko & Sargent 1997). The SMBH in M31, with an extraordinary mass of $\sim 1.4 \times 10^8$ M$_\odot$ (Bender et al. 2005), is well known to be in a highly quiescent state, Moreover, there is virtually no evidence of recent massive star (i.e., O- and B-types) formation in the circumnuclear region (Brown et al. 1998). These two facts conspire to make the ionizing source of the nuclear spiral a longstanding puzzle. On the other hand, in spite of the large body of evidence that photoionization by an active nucleus (AGN) is generally responsible for exciting LINERs, additional ionization/excitation mechanisms, such as radiation of old stars, shocks, cosmic-ray heating, etc., are often invoked (or required) to interpret observational details (cf. Ho 2008 for a review). Such mechanisms may in fact be prevalent in LINERs, but to what extent they are at work, after the leading role of AGN radiation, remains a critical open issue. M31 provides the nearest, quiescent (i.e., free of an AGN and active star formation) view of a LINER, allowing us to assess the relative importance of various ionization/excitation mechanisms. *HST* observations are essential to derive the necessary information, as described below.

2 Program objectives

We herein propose an *HST* mapping of the optical emission lines from the nuclear spiral in M31, in order to study its detailed spatial structure and possible ionization/excitation mechanisms. Specifically, our proposed observations will cover a field of $\sim 160'' \times 160''$ (600 pc$\times$600 pc) centering on the nucleus, mapping the [O II]λ3727, [O III]λ5007, Hα λ6563, [N II]λ6583 via appropriate WFC3/UVIS narrow-band filters (see Table 1).
Spatial structure In the aforementioned physical scenario, an effective evaporation of the nuclear spiral requires that it consist primarily of individual small gas clouds of sizes $\lesssim$1 pc, such that the mean free path of conducting electrons is shorter than the scale-length of temperature variation (Li et al. 2009). Resolving such clouds therefore demands for a sub-arcsec angular resolution that are only feasible with *HST*. The limitation of ground-based observations, at best with a seeing of $1''$-$2''$, is demonstrated in Fig. 2, in which a portion of the nuclear spiral in Hα+[N II] emission, observed with a $2''$-resolution (Devereux et al. 1994), is compared to an *HST* ACS/HRC/F330W image of the same region. In the *HST* image, the nuclear spiral clearly manifests itself as extinction features against the bulge starlight, which exhibit a variety of fine structures down to the image resolution of $\sim 0.''1$. The surface brightness of some features in the *HST* image is more than an order of magnitude higher than in the ground-based image.

Our proposed *HST* mapping aims at resolving the nuclear spiral into fine structures, such as discrete cloudlets and filaments. The measured line intensities and their ratios will provide direction information about the density, pressure, volume filling factor and ionization state. The moderate inclination of the nuclear spiral allows us to sort the relative positions of discrete structures with little ambiguity. The positional dependency of the gas density and ionization structures can then be studied. Obtaining such knowledge is very difficult, if not impossible, for distant LINERs. While extinction features might suffice to trace the overall organization of the nuclear spiral and provide complementary information on the density of dusty neutral gas (probably sitting in the cores of dense clouds), emission lines are a better tracer of fully ionized clouds or ionized surface layers. Such knowledge is useful to constrain dynamic formation models for the nuclear spiral (e.g., Stark & Binney 1994; Maciejewski 2004), especially in view of a possible channel of transporting gas to the very central regions. *Ionization/excitation mechanism* The proposed observations will allow us to derive the physical conditions of the gas on scales of $\lesssim$1 pc: the pair of the line ratios [O III]λ5002/[O II]λ3727-[N II]λ6583/Hα provides the conventional diagnostics for the ionization/excitation state. The derived quantities can then be confronted with theoretical models, such as photoionization, collisional ionization, or both (e.g., Viegas-Aldrovandi & Gruenwald 1990).

Notwithstanding the lack of ionizing photons from the SMBH and massive stars, a number of alternative ionizing sources can be invoked. In particular, UV photons from post-AGB stars are the most likely source of photoionization (Binette et al. 1994; Li et al. 2009); such stars *in situ* have been resolved by *HST* (Brown et al. 1998). It is therefore readily feasible to model their UV radiation to constrain the ionization parameter that is the essential parameter in photoionization models. The [O III]λ5002/[O II]λ3727 ratio is an excitation indicator sensitive to the ionization parameter of a radiation field by post-AGB stars (Binette et al. 1994), and hence is useful to assess the importance of photoionization. Collisional excitation mechanisms, such as shocks (Shull & Mckee 1979), thermal conduction (Nipoti & Binney), and cosmic-ray heating (Gruenwald & Viegas-Aldrovandi 1987) can also be examined. The latter, in particular, is energetically most viable (Li et al. 2009); extended radio continuum emission, albeit observed with substantially poorer angular resolutions, exhibits a probable counterpart of the nuclear spiral (Walterbos & Gräve 1985; Hoernes, Beck & Berkhuijsen 1998), suggesting a role of cosmic-rays. The cosmic-rays may originate from Type Ia supernovae or the radiatively inefficient accretion of the SMBH. The [N II]λ6583/Hα ratio is expected to be much stronger in the case of collisional excitation (e.g., cosmic-ray heating; Gruenwald & Viegas-Aldrovandi 1987) than in photoionization, a result of an enhanced partially ionized zone and a higher gas temperature. While ground-based observations already revealed a relatively high intensity ratio of [N II]/Hα of $\sim$2 across the nuclear spiral (Rubin & Ford 1971; Ciardullo et al. 1988), the measurement is diluted by at least a factor of ten in spatial resolution. Confusing the partially ionized and fully ionized zones, for example, will result in an underestimate of the [N II]/Hα ratio. Only the proposed *HST* observations have the full resolving power to minimize such effect.

Table 1: Log of proposed narrow-line mapping

Line	Filter[a]	Proposed exposure	Flux limit[b]
[O II]λ3727	F373N/F390M	2700 s	6.4e-17
[O III]λ5007	F502N/F547M	5400 s	4.5e-17
Hα λ6563	F656N/F665N	2700 s	1e-16
[N II]λ6583	F658N/F665N	2700 s	8.5e-17

[a] On- and off-band; [b] In units of ergs s^{-1} cm^{-2} A^{-1} $arcsecond^{-2}$ for a signal-to-noise ratio of 5.

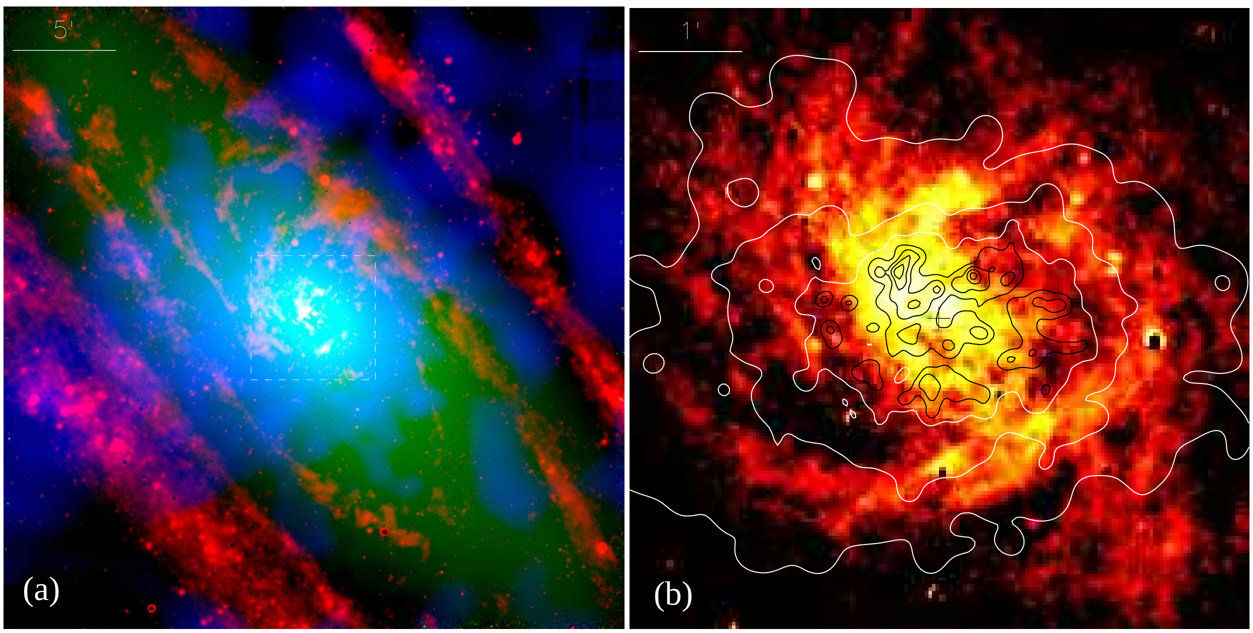

Figure 1: (a) Tri-color image of the central 30′ by 30′ (6.8 kpc by 6.8 kpc) of M31. *Red*: *Spitzer*/MIPS 24 μm emission tracing interstellar dust primarily residing in spiral arms; *Green*: 2MASS K-band emission tracing the old stellar populations; *Blue*: *Chandra*/ACIS 0.5-2 keV emission tracing the diffuse hot gas (Li & Wang 2007). Note the elongated morphology of the diffuse X-ray emission indicating a bulge outflow. The dashed box outlines the central 6′ by 6′, a region further shown in (b). (b) Intensity contours of the 0.5-2 keV diffuse emission overlaid on the Hα+[N II] emission (Devereux et al. 1994). The plus sign marks the M31 center.

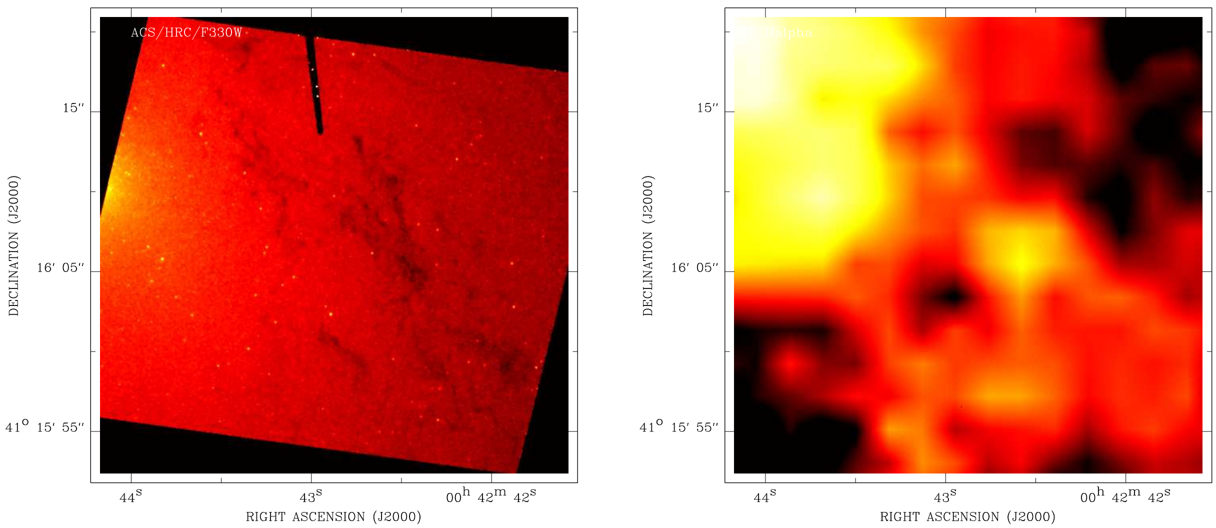

Figure 2: Comparison of the ability of resolving fine structures of the nuclear spiral with (a) HST and (b) ground-based Hα+[N II] observations.

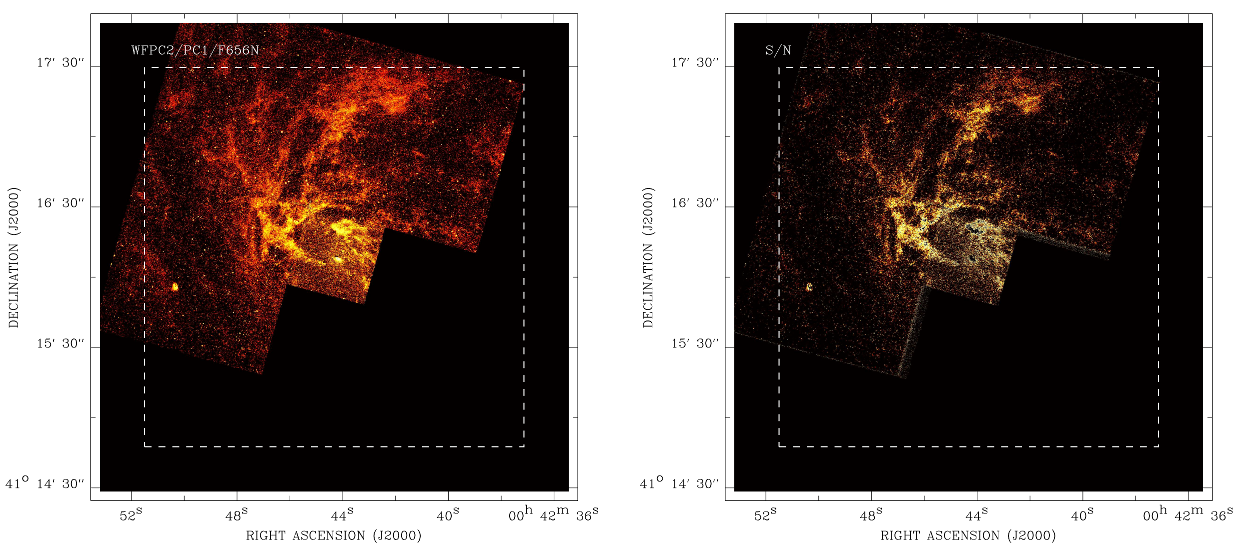

Figure 3: (a) An *HST* WFPC2/F656N image of the nuclear spiral. (b) A signal-to-noise map as achieved in (a), showing features with a S/N greater than 5. The dashed box, with a size of $162'' \times 162''$, illustrates the field of view of the proposed WFC3/UVIS observations.

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Description of the Observations

The newly available instrument WFC3, with its multiple narrow-line filters, is ideal for our proposed program. We will use a single WFC3/UVIS field to cover the central $\sim 150'' \times 150''$ about the M31 nucleus. This field is sufficient to cover the brightest features of the nuclear spiral (see Fig. 3), which spans a diameter of $\sim$600 pc comparable to the typical linear size of LINERs, e.g., observed in the Palomar survey (Ho et al. 1997), justifying a meaningful comparison. While the strength of the nuclear spiral appears highly asymmetric about the M31 center, we choose to obtain a symmetric, unbiased field of view. While an example field of view is illustrated in Fig. 3 with a roll angle of zero degree, we place no constraints on the exact roll angle.

1 Filter Selection

The WFC3/UVIS filters to be used are summarized in Table 1. In total there are 4 lines to be observed and 7 filters to be used, including three off-band continuum filters (several lines share a common off-band filter). As described in the above, pairs of the observed lines will provide the physical properties of the ionized gas: [O III]λ5002/[O II]λ3727 and [N II]λ6583/Hα. These lines are among the strongest optical lines of LINERs in general. While [O III]λ5002 and [O II]λ3727 have a substantial wavelength separation, the small and well-determined extinction across the nuclear spiral makes the correction of reddening less crucial; the other pair of lines has a small wavelength separation. We choose the closest possible off-band filters to optimize continuum subtraction. We also make sure that the blueshift does not bring irrelevant lines into the off-band filters. Most of the selected on-line filters require a velocity range of (-400 km/s, 400 km/s). Whereas the systemic velocity of M31 is -300 km/s, most regions across the nuclear spiral are known to have a line-of-sight velocity between (-400 km/s, -150 km/s) (Rubin & Ford 1971). Assuming a line centroid of -300 km/s and a velocity dispersion of 50 km/s (typical of the nuclear spiral), for example, results in a loss of throughput of only <6%.

2 Exposure Estimation

We estimate the required exposure time based on relevant existing WFPC2 observations (see *Justify Duplications*). The WFPC2 F656N observation (3600s) gives a S/N=5 flux limit for the combined Hα and [NII] line emission as 1.3×10^{-16} $ergs\ s^{-1}\ cm^{-2}\ A^{-1}\ arcsecond^{-2}$. We also use the WFPC2/F547M observation to estimate the contributions in the F656N (Hα) and F658N ([NII]) bands, assuming a spectrum of K0V, typical for the M31 bulge. With the ETC, we estimate that an exposure of 2700 s (the total science exposure per orbit; see below) will allow us to achieve an almost same detection limit for the Hα line alone and a factor of 2 better for the [N II]λ6583 line, which is expected to be a factor of ~ 2 stronger (Ciardullo et al. 1988).

Both [O III]λ5002 and [O II]λ3727 lines have been detected in ground-based spectroscopic and imaging observations (e.g., Jacoby et al. 1985), with their ratios to the Hβ emission consistent with those typically found for LINERs. Taking a conservative estimate of the [O III]/Hβ ratio as 1 and assuming the case B value of Hα/Hβ $\approx$2.86, we expect an [O III] line emission flux to be 4.5 $\times 10^{-17}$ $ergs\ s^{-1}\ cm^{-2}\ A^{-1}\ arcsecond^{-2}$. With the ETC, we find that this flux limit can be achieve with a 5400 s exposure (two orbits) in the F502N observation at S/N=5. The [O II]λ3727 line is typically several times stronger. Therefore, a better detection limit can be obtained with the F373N filter in one orbit. For the three off-line continuum filters, we ask for one orbit per each filter to achieve the same S/N. In total, we request 8 orbits to achieve our science goal.

3 Observation Design

Each orbit will have the same exposure design. We intend to use a 3-point WFC3-UVIS-DITHER-LINE pattern, with the dither offsets of 2.33 and 3.33 pixels in the x and y directions. This 1/3 subpixel offset is chosen to optimize the PSF sampling. This pattern could also help to remove cosmic-rays. The exposure time for each pointing is 900 second. Therefore, the total exposure time for each orbit is 2700 second. The overhead incurred during each orbit is as follows: 1) 333 s for the guide-star acquisition and instrument setup, b) 2700 s science exposures, c) 232 s for UVIS overhead for preparing the second and third exposures. The total time used is 3265 s, which can be fixed into one orbit, according to the APT of the latest version.

4 Parallel Observations

We also intend to use the ACS as the Coordinate Parallel Observations. ACS is about 6 arcminutes away from the center of the WFC3. We will use the data to sample M31, complementing our ongoing multi-wavelength study of the galaxy.

Special Requirements

Coordinated Observations

Justify Duplications

Over the years there have been hundreds of *HST* imaging observations toward the central regions of M31, from IR to UV bands. Most of these observations were taken with broad-band filters. One such example is shown in Fig. 1. The only observations using filters similar to our proposed observations include: those with the F502N, as mentioned in the above; a 1800-sec observation with WFPC1/F658N filter; two observations (2300-sec and 1300-sec) with the WFPC2/PC1/F656N, a filter covering both Hα+[N II]λ6583 lines. Our proposed observations will provide separate measurements of both the Hα and [NII] lines as well as a more complete coverage of the nuclear region that we are interested in.

There are also two existing observations for the [O III] line: one with the WFPC2/F502N filter for 1000 sec and the other with the WFC3/F502N filter for 600 sec. Both observations show little sign of [O III] emission; the field of view of the WFPC2/F502N observations was placed southwest of the M31 center, sampling a small region of the bright features of the nuclear spiral. The WFC3 observation was placed on the M31 center but only with a field of view of $\sim 40'' \times 40''$. These observations are simply not deep enough to detect the [OIII] line emission.

Our observations will also complement the data that are going to be obtained with the MCTP, "A Panchromatic Hubble Andromeda Survey, which will use the WFC3/UVIS and WFC3/NIR broad-band filters to obtain stellar photometry in the northeast quadrant of M31. This survey will cover the center of M31.

To summarize, our proposed program using WFC/UVIS narrow-line filters will provide for the first time a sub-arcsec, systematic view for the multiple optical emission lines from the nearest LINER.

Past HST Usage and Current Commitments