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# IONIZED GAS IN THE CENTER OF M31

GEORGE H. JACOBY
Kitt Peak National Observatory; National Optical Astronomy Observatories[1]

HOLLAND FORD[2]
Space Telescope Science Institute

AND

ROBIN CIARDULLO[2]
University of California, Los Angeles; Space Telescope Science Institute
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## ABSTRACT

We present Hα + [N II], [S II], and [O III] CCD images of the nuclear bulge of M31 which show a striking spiral pattern of ionized gas extending to within a few parsecs of the nucleus. The mass of ionized gas is approximately 1500 $M_\odot$ and can easily be provided by mass lost from evolving stars. Comparison of the recombination rate with the ionizing flux expected from planetary nebula nuclei leads to the conclusion that evolved stars are insufficient to support the ionization. The filamentary appearance, small filling factor, and the strength of the [S II] lines suggest that some of the gas is heated by shocks. The geometry of the apparent spiral arms implies that much of the gas is in a plane which is tipped with respect to the disk of M31.

*Subject headings:* galaxies: individual — galaxies: nuclei — galaxies: structure

## I. INTRODUCTION

Optical emission lines observed near the nucleus of M31 were reported in the course of kinematic investigations by Lallemand, Duchesne, and Walker (1960), Munch (1960), and Rubin and Ford (1971). Keel (1983*a*) recently completed a study of the morphology of ionized gas in the center of bright spiral galaxies. He found that ionized gas is common in the centers of normal spirals and suggested that processes occurring in active galaxies may occur to some extent in all galaxies.

The existence of gas in the center of M31 was suggested by the pictures of spiral dust lanes near the nucleus (Johnson and Hanna 1972; Kent 1983; McElroy 1983) and by the frequent association of gas and dust. Furthermore, the evolving stars in M31's bulge (Ford and Jacoby 1978*a*) will eject approximately $8 \times 10^9$ $M_\odot$ during a Hubble time (Jacoby 1980). Unless this gas turns into stars (Faber and Gallagher 1976; Jura 1977) or is lost through a galactic wind (Mathews and Baker 1971; Bregman 1980), some of the gas will accumulate near the nucleus.

If gas is present in the center of M31, some fraction of it will be ionized by the diffuse UV radiation which has been observed in the bulge. Wu *et al.* (1980) reported extended UV emission in the bulge of M31, and Deharveng *et al.* (1982) found that this emission followed the optical light distribution of the bulge. This radiation most likely comes from evolved stars such as hot subdwarfs and blue horizontal-branch stars.

Rubin and Ford (1971) discuss in detail the dynamics of this ionized gas along the major axis and within 400 pc of the nucleus. Here we report on the global morphology of the gas as seen in the emission lines of [O III] λ5007; Hα λ6563 + [N II] λλ6548, 6583; and [S II] λλ6717, 6731.

## II. OBSERVATIONS

During the course of a nova survey and a program to measure the luminosity function of planetary nebulae, we repeatedly observed fields in the center of M31 with an RCA CCD on the Kitt Peak No. 1, 0.9 m telescope in the f/7.5 configuration. Seeing was typically better than 1".5, so the seeing disk was somewhat undersampled by the 0".86 pixels. A journal of the observations, taken on and off the emission lines of Hα λ6563 + [N II] λλ6548, 6583; [O III] λ5007; and [S II] λλ6717, 6731, is given in Table 1. For all three emission lines, the off-line exposures were chosen to yield a signal-to-noise ratio equal to that of the on-band images.

Since the off-band frames were generally displaced by several pixels from the on-band images, we first shifted these frames to align the stars. The off-band intensities were then scaled by exposure time and bandwidth to match the expected values in the on-band images. An additional small scaling factor was

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[2] Visiting Observer, Kitt Peak National Observatory.

TABLE 1
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| Date | Picture | Filter/FWHM | Exposure (s) |
|---|---|---|---|
| 1983 Oct 10/11... | Hα + [N II] | 6563/80 | 5400 |
| 1983 Oct 10/11... | Hα + [N II]/[S II] offband | 6204/150 | 3240 |
| 1983 Oct 12/13... | [S II] | 6727/80 | 5400 |
| 1982 Sep 23/24... | [O III] | 5009/22 | 3600 |
| 1982 Sep 15/16... | [O III] offband | 5200/104 | 900 |

next applied to adjust this intensity and to provide the best intensity match possible. Finally, the continuum starlight was removed by subtracting the off-band from the on-band frames.

Because the actual flux ratios between the emission and off-line bandpasses are not known *a priori*, the subtractions are necessarily approximate. Each subtraction was performed iteratively by varying the scaling factor until the difference picture had a flat background. This criterion may introduce a systematic underestimate of the emission fluxes if there is diffuse emission across the field. The error could be significant at the very low surface brightness levels considered here (on the order of 1% or less of the continuum flux).

The signal-to-noise ratio required to detect the line emission over the bright nuclear background is high. In our unsubtracted images, the signal-to-noise ratio over most of each frame is greater than 250 per pixel. Large-scale variations due to flat fielding, however, introduce global variations on the order of 0.50%.

Figures 1*a*–1*c* (Plate 2) show the difference frames of Hα + [N II], [S II], and [O III], respectively. Figure 1*d* shows the unsubtracted Hα + [N II] frame for reference. The Hα + [N II] difference picture shows an incomplete ellipse of ionized gas with approximate dimensions of 180″ × 250″ (585 pc × 810 pc). The emission has the appearance of two spiral arms which emerge from a "bar" and almost wrap up into an elliptical ring. The gas appears very filamentary with several bright arcs northeast of the nucleus. The strongest [S II] emission appears to come from the bright filaments 5″ to 15″ northeast of the nucleus. The [O III] emission is strongest in the pair of filaments north of the nucleus. The apparently very weak [O III] emission suggests that the gas is in a low-excitation state. However, a subsequent measurement of the filter transmission curve showed that [O III] emission at M31's systemic velocity ($-300$ km s$^{-1}$) falls at the filter's half-peak transmission point. Consequently, emission at velocities more negative than the systemic velocity will be reduced by a factor of 2 or more. The [O III] picture also shows a large number of stellar images which are planetary nebulae (cf. Ford and Jacoby 1978*b*).

Because the off-band frames for Hα + [N II] and [S II] were taken at a shorter wavelength than the on-band frames, dust clouds appear with more contrast in these pictures. Consequently, when we subtract off-band from on-band, absorption due to dust might produce false positive images which could mimic diffuse emission. However, there are three reasons why we believe this effect is unimportant. First, our on-band [O III] frames were taken at a shorter wavelength than their off-band counterparts, thus reversing the effects of differential reddening. Comparison of the difference frames of [O III] and Hα + [N II], however, show the same basic emission patterns. Second, the [S II] difference was obtained using the same off-band frame as the Hα + [N II] difference (see Table 1). If differential reddening effects were dominant, the [S II] difference would appear substantially the same as the Hα + [N II] difference, but with 50% greater contrast due to the greater wavelength baseline. The frames, however, look quite different. Third, none of the difference images correlate well with the patterns of dust in M31 (see § III*c*). From these analyses, we conclude that the observed patterns are indeed due to gas emission and not to reddening from scattered dust clouds.

The Hα + [N II] emission line flux levels were derived using observations of the standard stars BD +25°3941 and Hiltner 600. The shape of the filter transmission curve, which must be convolved with the continuum stellar spectra for absolute photometry, was found to be well represented by a rectangular bandpass having a full width at half-maximum of 80 Å. The two standards agreed in their derived flux-per-count ratio to within 1%.

The total flux across the M31 image was obtained by summing all the flux above the zero background level in a 235″ × 235″ box centered on the nucleus. The majority of intensity spikes due to incomplete star subtraction, cosmic rays, and defects were set to zero by examining the frame's intensity histogram and rejecting all pixels outside the primary information regime which was considered to be within 4 standard deviations from the mode of the histogram. Any remaining bad pixels have little effect on the net flux.

The background was determined from a 25″ × 240″ strip along the eastern edge of the frame. The derived reddening-corrected flux above the Earth's atmosphere over a bandpass centered on Hα + [N II] was found to be $3.2 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, assuming $E(B-V) = 0.11$. For a distance of 670 kpc, this corresponds to a total luminosity of $1.7 \times 10^{39}$ ergs s$^{-1}$. As noted above, the flux may be systematically low if diffuse emission is present across the nuclear bulge.

## III. DISCUSSION

### *a) Mass of Ionized Gas*

We assume that the derived flux is primarily due to [N II] with the ratio of $I(\lambda 6583) + I(\lambda 6548)/I(H\alpha) = 2.6$, and that the electron density is approximately 1000 cm$^{-3}$. These are typical values found for other normal spirals by Keel (1983*b*). Rubin and Ford (1971) found that the average ratio of [N II] to Hα is closer to 3 in M31, but their observations were position dependent and somewhat uncertain due to the limits of the photographic spectra and the possibility of underlying stellar Hα absorption. They used the [S II] $I(6717)/I(6730)$ ratio to estimate an electron density of approximately 1000 cm$^{-3}$. When these density estimates are combined with our measured flux, the mass of ionized gas is 1500 $M_\odot$. If we assume the emitting volume is confined to a disk having a thickness of 200 pc in the plane of the galaxy, the volumetric filling factor is $3 \times 10^{-7}$, implying that the gas is highly filamented.

It is interesting to consider the source of the ionized gas. Ford and Jacoby (1978*a*) found 312 planetary nebulae in the bulge of M31 and derived a mass return rate of 0.026 $M_\odot$ yr$^{-1}$. As a result of improved estimates of the number of planetary nebulae in the M31 bulge, Jacoby (1980) found that this rate should be approximately doubled. The observed ionized gas will accumulate in approximately 30,000 yr if all the gas is retained near the center. Even if only a small fraction of the gas is retained, the evolving stars are such an abundant source of mass that they most likely are the origin of the observed gas.

Clearly the observed mass is much smaller than that which would accumulate over a Hubble time. Unless the remainder of the mass has been converted to stars, or is neutral, most of the returned mass has been lost to the galaxy, possibly in the form of a galactic wind (Mathews and Baker 1971). Gallagher and Hunter (1981) have shown that dust clouds near the center of M31 have significantly greater mass ($10^4$ $M_\odot$ per cloud) than the ionized material (1500 $M_\odot$). The dominant state of the gas in the center of M31 is therefore neutral and a considerable amount of material must be contained in the clouds.

### *b) Ionization Source*

Deharveng *et al.* (1980) measured the flux from the bulge at 1990 Å using a balloon-borne imaging detector. Within a 10′

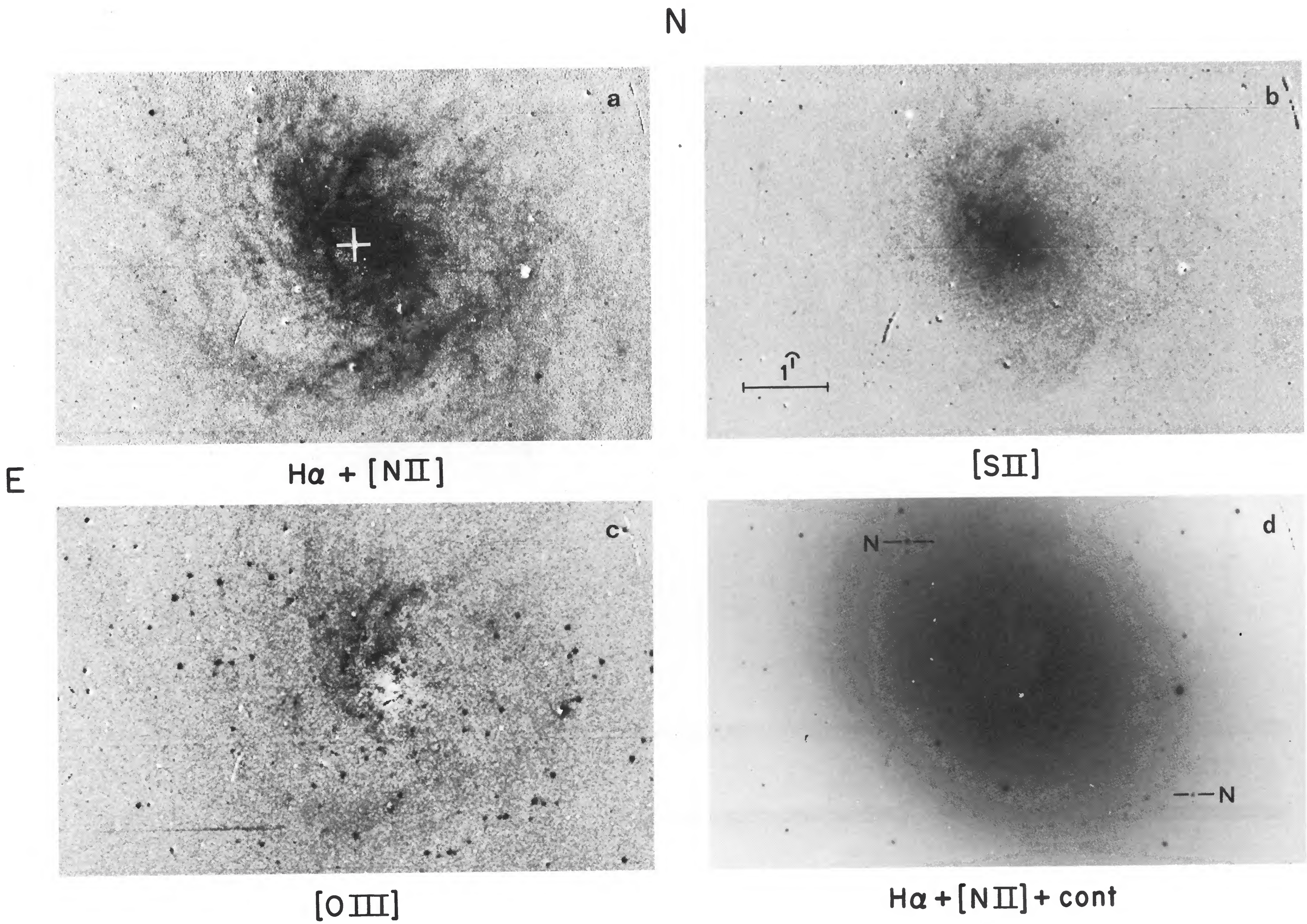


FIG. 1.—Images of the ionized gas in the center of M31: (*a*) Hα + [N II]; (*b*) [S II] λλ6717, 6731; (*c*) [O III] λ5007; (*d*) Hα + [N II] + continuum. At the position of S And (1885) (16".3 west and 4".7 south of the nucleus; Copeland 1886) there is strong Hα + [N II] emission, but this may be coincidental. In (*a*) the position of the nucleus is marked by a cross. In (*d*), two novae are indicated.

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field, they found the dereddened flux to be $4.7 \times 10^{-13}$ ergs $cm^{-2}\ s^{-1}\ Å^{-1}$; Code and Welch (1979) reported a similar flux derived from *OAO 2* observations. Deharveng *et al.* (1982) concluded that the UV flux is due to evolved stars (probably blue horizontal-branch stars) rather than hot young stars because the UV flux distribution follows the optical light distribution of the bulge.

We can estimate the number of evolved stars required to maintain the ionization rate and the luminosity of the ionized gas in the bulge of M31. The dominant contributors to the far-UV flux are the intermediate-age, planetary-nebula central stars having luminosities of approximately 5000 $L_\odot$ and ages from 5,000 to 12,000 yr. Typical temperatures and radii for these stars are $T_* \approx 80{,}000$ K and $R_* \approx 0.37\ R_\odot$ (Iben *et al.* 1983). If these stars radiate as blackbodies, they each generate $3.87 \times 10^{47}$ photons per second shortward of 912 Å.

The recombination rate, $R$, can be estimated from the observed $H\alpha$ flux:

$$R = N_{\mathrm{H}^+} N_e \alpha_B \epsilon V ,$$

where $\alpha_B$ is the recombination coefficient assuming an optically thick gas, and the quantity $\epsilon V$ is the volume occupied by the radiating material such that:

$$\epsilon V = \frac{4\pi D^2 F_{\mathrm{H}\beta}}{\alpha_{\mathrm{H}\beta}{}^{\mathrm{eff}} N_{\mathrm{H}^+} N_e h\nu_{\mathrm{H}\beta}} ,$$

and $D$ is the distance to M31. Combining these two equations and noting that $F_{\mathrm{H}\alpha} \approx 2.87\ F_{\mathrm{H}\beta}$, we find that $R \approx 3.5 \times 10^{50}$ recombinations per second, or 905 times the ionizing photon rate from a single, hot, central star.

If we assume that the ionizing stars are distributed throughout the bulge and that the gas is uniformly distributed in a thin plane, then only half of the radiated photons can interact with the gas. The remainder are radiated in a direction away from the plane. Then at least 1810 ($=2 \times 905$) central stars are required to balance the estimated recombination rate. Many more stars are needed if the geometry of the emitting volume is clumpy and filamented as suggested by the small filling factor.

We can estimate the number of intermediate-age central stars present in the bulge of M31 based on the number of planetary nebulae observed. Ford and Jacoby (1978*a*) found 312 planetary nebulae in the bulge of M31 and corrected this sample for survey incompleteness and the effects of dust obscuration to derive a population of 778 bright planetary nebulae. The luminosity function from the Magellanic Clouds (Jacoby 1980) can be applied to account for fainter nebulae, yielding an estimate of 5800 planetary nebulae in the bulge of M31.

If a typical lifetime for a planetary nebula is 25,000 yr, the intermediate-age group includes 28% of the total, or 1600 planetary nebulae. Consequently, in the case of an idealized geometry where the ionized gas consists of a uniform sheet, there might be enough planetary nebulae to ionize the gas. In the more realistic case where the central stars are partially veiled by their own envelopes and the gas is highly filamented, it seems unlikely that the planetary nebulae are sufficient to ionize the gas.

### *c) Morphology*

The most conspicuous feature in the $H\alpha$ + [N II] image is the apparent spiral arm which traces northeastward from a central "bar," bends through west to the south, and finally merges with a second arm which appears to emanate from the southwest side of the central bar. The arms are also faintly visible in the other images. These arms may also be viewed as a single elliptical ring.

Careful comparison of our pictures with the prominent dust lanes seen in McElroy's (1983) short-exposure, blue photograph of M31 and the enhanced images in Figure 2*b* of Gallagher and Hunter (1981) shows that although there is no strong correlation between the positions of the ionized gas and the dust, a weak, possibly coincidental, relationship exists. This is most easily seen for the arc of emission north of the nucleus. Rubin and Ford (1971) note a similar enhancement of emission at this and other crossings of dust lanes.

The $H\alpha$ + [N II] picture shows a barlike structure which lies along the major axis. Because M31 has a large inclination to the line of sight (77° at a 39° position angle; Rubin and Ford 1971; Baade and Arp 1964), this feature can be explained by the projection of a roughly circular disk. However, if the elliptical ring is truly planar, then its plane is most likely tipped with respect to the disk of M31. Otherwise, the projection into the disk rectifies the ring by a factor of 4.4 in the direction of the minor axis. The feature then becomes a highly elongated ellipse with an axial ratio of 6 to 1. The geometry strongly suggests that the ionized gas comprising the ellipse is in a plane tipped relative to the disk of M31.

It is difficult to see how the gas ejected from the bulge distribution of evolving stars can settle into a tipped plane if the underlying potential is axisymmetric. However, several studies (e.g., Matsumoto, Murakami, and Hamajima 1977; Stark 1977) have suggested that the changing position angle of M31's optical major axis in the nuclear bulge can be understood in terms of an asymmetrical structure, such as a barlike distribution. Furthermore, Brinks (1984) suggests that the overall velocity pattern of the gas and stars in the bulge "can be reconciled with the concept of a bar-like potential if the major axis of the bar is approximately aligned with or at right angles to the line of nodes of the disk." The asymmetrical potential caused by the bar could provide the mechanism for sustaining a stable tipped plane, or the tipped plane may originate from a central bulge which is tipped relative to the plane of the disk (Ruiz 1976). A bar or tipped central bulge aligned along the major axis would also provide a natural explanation for the alignment of the kinematical major axis of the ionized gas and the optical major axis (Rubin and Ford 1971). We also note that the gas kinematics in the innermost 600 pc of the Galaxy have been interpreted in terms of a tilted disk (cf. Liszt and Burton 1980; Lake and Norman 1982).

Based on long-slit spectra obtained at a number of position angles, Rubin and Ford (1971) concluded that the gas in this region of M31 is subjected to a large-scale expansion superposed on the general rotation field. They also suspected the presence of motion perpendicular to the plane, especially near the bright emission north of the nucleus. Additional kinematic data for positions selected along the elliptical ring and the bar are needed to test the possibility that the ring is a single dynamical entity and may be in a tipped plane.

Apart from the spiral pattern, the overall impression of the $H\alpha$ + [N II] image is that of a highly filamented medium such as is seen in supernova remnants. Keel (1983*c*) found suggestions of Crab Nebula morphologies in several more distant spirals. Such structures, which are conspicuous in the center of M31, imply that the gas near the nucleus is heated by shocks, possibly due to infalling material (Rubin and Ford 1971), or by

Type I supernovae such as S And, which are known to occur in the bulge. Unlike more active galaxies, M31's velocity field argues against any form of gas ejection from the nucleus.

Although our images are generally too noisy to derive spatially resolved line ratios, qualitatively the ratio of [S II] to H$\alpha$ + [N II] is high in the central 50″ and somewhat lower in the arms. This may be further evidence for a nonthermal energy source near the nucleus (van der Kruit 1972; Pooley and Kenderdine 1967).

## IV. CONCLUSIONS

We have shown that the technique of subtracting very high signal-to-noise ratio images is an effective method of isolating the structure of ionized gas near the nuclei of galaxies. Our pictures of M31 show a striking spiral pattern of ionized gas extending to within a few parsecs of the nucleus and possibly residing in a plane tipped with respect to the disk of the galaxy. We have shown that, although the mass of the ionized gas is only 1500 $M_\odot$ and can easily be provided by evolving stars, the ionizing flux from planetary nebula nuclei is insufficient to ionize the gas. The filamentary appearance of the gas, its small filling factor, and the strength of the [S II] lines suggest that shocks may play an important role in the gas heating.

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ROBIN CIARDULLO and HOLLAND FORD: Space Telescope Science Institute, Homewood Campus, Baltimore, MD 21218

GEORGE H. JACOBY: Kitt Peak National Observatory, P.O. Box 26732, Tucson, AZ 85726