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THE FIRST ULTRAVIOLET SPECTROPOLARIMETRIC STUDY OF NGC 1068

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ABSTRACT

We present the first ultraviolet spectropolarimetric observations of the Type 2 Seyfert galaxy NGC 1068 obtained by the Wisconsin Ultraviolet Photo Polarimeter Experiment (WUPPE). In this communication we discuss the continuum polarization in the ultraviolet. Shortward of 2500 Å the polarization becomes constant at 16% at a position angle of 112°. This is in general agreement with the 1983 prediction of Miller and Antonucci and their thick torus model, in which a hidden Type 1 Seyfert nucleus is seen in light scattered by electrons outside the obscured nuclei.

Subject headings: galaxies: individual (NGC 1068) — galaxies: Seyfert — polarization

1. INTRODUCTION

The basic distinction between Seyfert galaxies of Types 1 and 2 is that the former have very broad ($\sim$3000 km s^{-1}) components in their permitted emission lines in addition to the narrow ($\sim$350 km s^{-1}) components of both permitted and forbidden lines common to both types (Osterbrock 1991). Prototypical examples of Types 1 and 2 are NGC 4151 and NGC 1068, respectively. The discovery of polarization in some Type 2 Seyfert galaxies (Walker 1968; Visvanathan & Oke 1968) was taken as direct evidence of the nonthermal origin of some of the radiation from the galactic nucleus. Spectropolarimetry of NGC 1068 by Angel et al. (1976) showed that the continuum polarization rises from $\sim$2% in the red to $\sim$7% in the blue, which they interpreted as scattering by dust grains. The interpretation is complicated, however, by the contamination due to light from the stellar component of the galaxy itself. In order to determine the intrinsic polarization of the nucleus alone, Miller & Antonucci (1983, hereafter MA83) estimated the unpolarized background galactic starlight using the spectrum of M32 as a model. With this stellar contribution subtracted, MA83 found a polarization for the nucleus to be $\sim$16% over the entire visible wavelength range. Based on the wavelength independence of polarization they concluded that the polarigenic mechanism is probably electron scattering. Based on further analysis of the data Antonucci & Miller (1985, hereafter AM85) found that the polarized flux [$P(\lambda) \times F_\lambda$] in NGC 1068 has broad H I, He I, and He II emission line components similar to a Type 1 Seyfert intensity spectrum. They suggested that a Type 1 Seyfert nucleus is present at the center of NGC 1068 but is hidden from direct view by a thick disk. Material outside the nucleus and near the disk axis reflects and polarizes some of the nuclear light. AM85 went on to suggest in general that the difference between Types 1 and 2 is an inclination effect. Type 1 Seyfert galaxies are just those which are viewed along a line of sight sufficiently close to the axis of the disk to afford a direct view of the nonthermal engine and thus the so-called broad-line region (BLR). Type 2 Seyfert galaxies have the direct view of the BLR obscured by a thick disk. Miller & Goodrich (1990) showed that four of eight highly polarized Seyfert 2 galaxies also exhibited hidden Seyfert 1 nuclei and that in the other four the detection of the hidden nucleus was probably below their detection threshold.

The MA83 electron scattering hypothesis can be tested by observations of the polarization in the ultraviolet. There are several advantages to UV observations. First, most of the contaminating stellar light comes from cool giant stars which are very much fainter in the UV. Second, any component of interstellar polarization is lower at shorter wavelengths (Clayton et al. 1992). Third, the nuclear radiation from the central engine is expected to be stronger in the UV. Taken together, all these effects should make contamination corrections to UV polarization observations shortward of $\sim$2500 Å much less important than in the visual. If the polarization is due to electron scattering both the percent polarization and the position angle should remain constant. In this paper we present the first UV spectropolarimetric observations of the Seyfert 2 galaxy NGC 1068 which were obtained with the Wisconsin Ultraviolet Photo Polarimeter Experiment (WUPPE). These observations enable us to (1) check the validity of the stellar contamination correction of MA83 to see if the intrinsic polarization of the nucleus is in fact near 16% and (2) establish whether or not the polarization is actually wavelength independent as expected for electron scattering.

2. OBSERVATIONS

The observations were made during the 1990 December 2–9, Astro-1 mission of the space shuttle Columbia. WUPPE is a 0.5 m telescope with a Cassegrain spectrograph and polarization analyzing optics. Polarization modulation is accomplished by switching between six differently oriented half-wave plates located in a filter wheel just behind the entrance aperture. The light then is separated into two beams of orthogonal linear polarization by a MgF_2 Wollaston prism. A Monk-Gilleson spectrometer images these two spectra on a CsTe photo cathode microchannel plate intensifier. The intensifier output is integrated and read out by parallel Reticon self-

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scanned diode arrays. From the sum and difference of these two spectra the flux, percent polarization, and position angle as a function of wavelength are obtained between 1400 and 3200 Å. The spectroscopic resolution is ~12 Å. The polarization spectra are binned in wavelength to obtain a specified constant polarization error, ~1.0% in the case of NGC 1068. Calibrations of polarization efficiency, instrumental polarization, position angle registration, and flux sensitivity have been determined by a combination of preflight laboratory measures and in-flight standard star observations. The data are corrected for telemetry errors, thermal background, cosmic-ray hits, pointing corrections, second-order contamination, and instrumental polarization. The calibration and reductions will be described in detail in a forthcoming paper by Nordsieck et al. (1993).

The calibration and reduction procedures have been developed to treat observations of stellar sources and result in reliable flux and polarization measures of such sources. The reduction of flux limited diffuse sources requiring longer integration times is, however, complicated by pointing instabilities encountered during the mission. This does not significantly affect the continuum polarization determination, but care must be excercised in analyzing the spectral distribution and line profiles. The insensitivity of the polarization determination is, of course, due to the fact that it is a differential measurement. In this paper we use a flux calibration based upon the *IUE* measurements of NGC 1068.

The observation of NGC 1068 presented here was obtained on 1990 December 8 (JD 2,448,234.52). The galactic nucleus was centered in a 6″ × 12″ aperture and an integration time of 1472 s, all during orbital night, was obtained. The results are shown in Figure 1. Figures 1*a* and 1*b* show the percent polarization and the position angle of that polarization as a function of wavelength respectively, while Figure 1*c* shows the spectrum plotted as log F_λ.

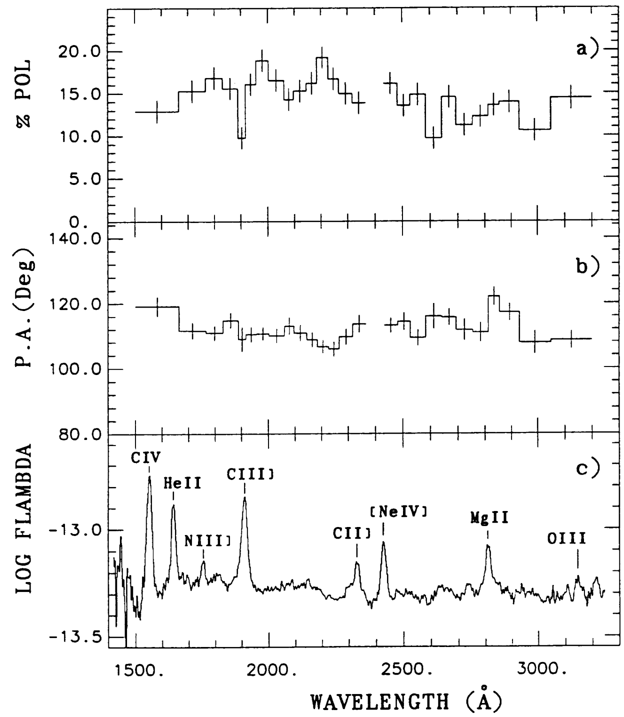

FIG. 1.—Wisconsin Ultraviolet Photo Polarimeter Experiment observations of the Type 2 Seyfert galaxy NGC 1068 from 3200 to 1500 Å obtained during the 1990 December Astro-1 mission; (*a*) percent polarization, (*b*) position angle, and (*c*) intensity (log F_λ) spectra. The percent polarization and position angle spectra are coarsely binned to achieve an internal error of 1.3%. In the intensity spectrum there are ~6 pixels per resolution element. The gap in the data near 2400 Å is due to a flaw in one of the detector arrays.

3. RESULTS

It is evident from Figure 1*a* that the polarization in the UV is large and nearly constant. These data are binned to achieve ±1.3% internal error in the polarization, which corresponds to wavelength intervals of the order of 100 Å. Based on the M32 model of galactic starlight used by MA83 we do not expect to see any significant flux contribution in the WUPPE aperture shortward of 2500 Å. The average polarization shortward of 2500 Å is 15.4% ± 2.2% while from 3200 to 2500 Å it is 12.9% ± 1.9%. This is in excellent agreement with the predictions of the MA83 electron scattering hypothesis.

Figure 1*b* shows the position angle of the polarization, θ, as a function of wavelength, binned in the same way as the percent polarization. The average θ from 3200 to 1500 Å is 112°.0 ± 3°.8 and has a slope of only 0°.8 ± 1°.6 per 1000 Å. Our value of θ is substantially larger than that found in the visible by MA83 or by Angel et al. (1976) and contradicts the straightforward interpretation that electron scattering is the only contributor to the UV polarization measured by WUPPE.

Any contribution by interstellar polarization has generally been assumed to be small. This assumption is based upon the various estimates indicating low interstellar extinction and the relatively small polarization measured in narrow forbidden lines. If we assume that the polarization seen by Bailey et al. (1988) in [O III] 4959 Å + 5007 Å, ~0.5% at ~150°, represents the interstellar component, the contamination due to interstellar polarization is unimportant. To explain the difference between our value of 112° with the MA83 value of 95° would require an order of magnitude larger degree of interstellar polarization. Also, since interstellar polarization is expected to decrease to the ultraviolet (Clayton et al. 1992), the position angle would have to be less than 95° not greater.

The most likely cause of the difference in position angle is the contamination introduced into the WUPPE measurements by the polarized NE elongation measured by Scarrott et al. (1991, hereafter SRWT91) and by Miller, Goodrich, & Mathews (1991, hereafter MGM91). The WUPPE measurements were carried out with a 6″ × 12″ aperture centered on the nucleus. The orientation of this aperture is shown in Figure 2, superposed on the visual isophotes and polarization map of SRWT91. The long dimension of the aperture (perpendicular to the dispersion) includes most of the NE elongation; it does not include any of the other polarized regions identified by MGM91. The polarization of the NE elongation in the *V* band was found by SRWT91 to be 2.33% ± 0.19% at a position angle of 134°.1 ± 2°.3. MGM91 found a position angle of ~125°, with the polarization increasing to the blue to a value of the order of 25% at 3600 Å. Integration over the WUPPE aperture using preliminary results from UIT ultraviolet images of NGC 1068 (Neff et al. 1991) indicates that the NE elongation contributes between 15% and 20% as much flux as the nuclear region. We therefore expect that the contribution to the total polarization flux by the NE elongation is unlikely to be greater than 8% (20% flux and 40% polarization) nor less than ~3% at this larger position angle. It should be noted that in the QU-plane the NE polarization vector is nearly orthogonal to the nuclear contribution; therefore the effect will be

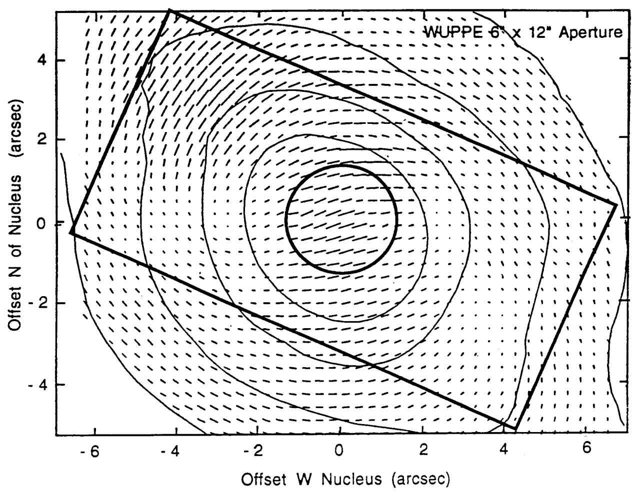

FIG. 2.—WUPPE 6″ × 12″ aperture centered on the V isophotes of Scarroti et al. The spectral dispersion runs perpendicular to the long dimension of the aperture. The degree of polarization over the field is indicated by lines on the polarization map. Also shown is the 2″.8 aperture used by Miller & Antonucci.

primarily one of rotating the position angle with little change in degree of polarization. Within the error estimates of the MA83 calculation and the WUPPE measurements the contamination due to the NE elongation can explain the position angle difference.

Figure 1*c* shows the flux spectrum of NGC 1068. The strong emission lines of C IV 1549 Å, He II 1640 Å, N III] 1750 Å, C III] 1909 Å, C II] 2326 Å, [Ne IV] 2423 Å, Mg II 2800 Å, and O III 3133 Å are marked. In addition, weaker lines of N IV] 1485 Å, Si II + [Ne III] 1805 Å, and He II 2733 Å may be present. A discussion of the spectral flux and line polarization will be presented in a subsequent paper. We note here only two features which are of significance to the discussion above. First, there is no evidence for a 2200 Å extinction bump. The signal-to-noise ratio in this spectral region is sufficiently high that it is possible to set an upper limit on the $(B-V)$ color excess of 0.1 mag for the contribution from a "standard" galactic extinction curve. This in turn suggests an upper limit of 2% interstellar polarization at V and 1% in the 2000 Å to 3000 Å region. The second comment concerns the polarized flux, $[P(\lambda) \times F_\lambda]$. The polarized flux eliminates direct unpolarized light. The WUPPE data show a flat polarized flux spectrum with no obvious spectral features. In particular, all the sharp emission lines are absent in the polarized flux, indicating the absence of interstellar polarization at a level that would effect the conclusions of this paper. The discussion of the possible presence of broad polarized line components will be presented in a subsequent paper following completion of the final flux calibration.

4. SUMMARY AND DISCUSSION

We have reported the first spectropolarimetric observations in the ultraviolet of a Type 2 Seyfert galaxy, NGC 1068. Shortward of 2500 Å the polarization is constant at 16% and P.A. 112°. After allowing for contamination due to the scattered light from the NE elongation, the observations are in good agreement with the predictions of MA83. Their procedure for estimating the contamination of the optical polarization by starlight seems to have been substantially correct. The most plausible mechanism for producing constant polarization over such a wide spectral range is electron scattering. While certain dust models and scattering geometries are capable of explaining a wavelength-independent polarization, it does not seem possible to also explain a flat polarized flux over the large spectral range covered by the combined MA83 and WUPPE measurements. For example, small particles can give Rayleigh-like scattering but the cross section will then vary as λ^{-4} and therefore produce two orders of magnitude variation in opacity. This could not result in a flat polarized spectrum. Thus the results of the WUPPE measurements of the ultraviolet polarization of NGC 1068 are consistent with the interpretation that the polarized radiation results from electron scattering of the hidden nuclear light.

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