

## NICMOS POLARIMETRY OF “POLAR-SCATTERED” SEYFERT 1 GALAXIES\*

D. BATCHELDOR<sup>1,2</sup>, A. ROBINSON<sup>3,4</sup>, D. J. AXON<sup>3,4,5</sup>, S. YOUNG<sup>3,4</sup>, S. QUINN<sup>3</sup>, J. E. SMITH<sup>6</sup>, J. HOUGH<sup>4</sup>, AND D. M. ALEXANDER<sup>7</sup>

<sup>1</sup> Department of Physics and Space Sciences, Florida Institute of Technology, 150 W. University Blvd, Melbourne, FL 32901, USA; [dbatcheldor@fit.edu](mailto:dbatcheldor@fit.edu)

<sup>2</sup> Center for Imaging Science, Rochester Institute of Technology, 54 Lomb Memorial Drive, Rochester, NY 14623, USA

<sup>3</sup> Department of Physics, Rochester Institute of Technology, 54 Lomb Memorial Drive, Rochester, NY 14623, USA

<sup>4</sup> Centre for Astrophysics Research, Science & Technology Research Institute, University of Hertfordshire, Hatfield AL10 9AB, UK

<sup>5</sup> School of Mathematical & Physical Sciences, University of Sussex, Falmer, Brighton BN2 9BH, UK

<sup>6</sup> Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK

<sup>7</sup> Department of Physics, Durham University, Durham DH1 3LE, UK

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### ABSTRACT

The nuclei of Seyfert 1 galaxies exhibit a range of optical polarization characteristics that can be understood in terms of two scattering regions producing orthogonal polarizations: an extended polar scattering region (PSR) and a compact equatorial scattering region (ESR), located within the circum-nuclear torus. Here we present NICMOS  $2.0\ \mu\text{m}$  imaging polarimetry of six “polar-scattered” Seyfert 1 (S1) galaxies, in which the PSR dominates the optical polarization. The unresolved nucleus ( $<0''.58$ ) is significantly polarized in only three objects, but five of the six exhibit polarization in a  $0''.58\text{--}1''.5$  circum-nuclear annulus. In Fairall 51 and ESO 323-G077, the polarization position angle at  $2\ \mu\text{m}$  ( $\theta_{2\ \mu\text{m}}$ ) is consistent with the average for the optical spectrum ( $\theta_v$ ), implying that the nuclear polarization is dominated by polar scattering at both wavelengths. The same is probably true for NGC 3227. In both NGC 4593 and Mrk 766, there is a large difference between  $\theta_{2\ \mu\text{m}}$  and  $\theta_v$  off-nucleus, where polar scattering is expected to dominate. This may be due to contamination by interstellar polarization in NGC 4593, but there is no clear explanation in the case of the strongly polarized Mrk 766. Lastly, in Mrk 1239, a large change ( $\approx 60^\circ$ ) in  $\theta_{2\ \mu\text{m}}$  between the nucleus and the annulus indicates that the unresolved nucleus and its immediate surroundings have different polarization states at  $2\ \mu\text{m}$ , which we attribute to the ESR and PSR, respectively. A further implication is that the source of the *scattered*  $2\ \mu\text{m}$  emission in the unresolved nucleus is the accretion disk, rather than torus hot dust emission.

*Key words:* galaxies: nuclei – galaxies: Seyfert – infrared: galaxies – polarization – scattering – techniques: polarimetric

*Online-only material:* color figure

### 1. INTRODUCTION

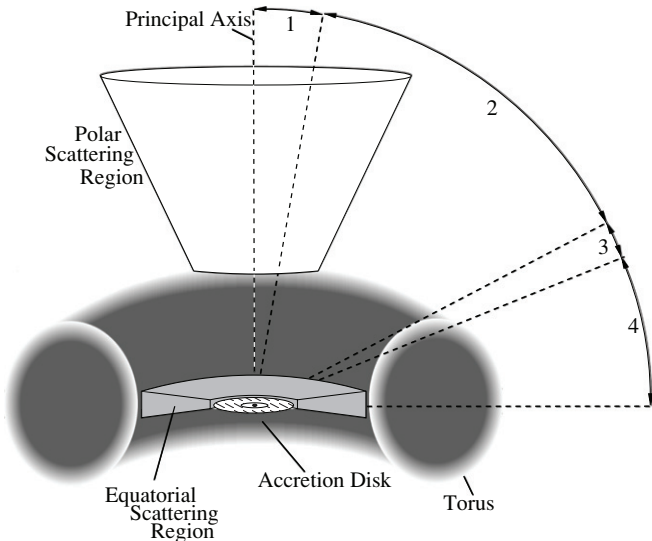
In the unified model for Seyfert galaxies (Antonucci 1993; Urry & Padovani 1995), Seyfert Type 1 (S1) and Type 2 (S2) nuclei are intrinsically the same type of object viewed at different orientations. In the S2’s, our direct line of sight to the nuclear continuum source and broad-line region (BLR) is blocked by a clumpy toroidal region of dusty molecular gas clouds, on scales of possibly just a few parsecs (Jaffe et al. 2004; Tristram et al. 2007). Spectropolarimetry played a pivotal role in establishing this picture through the detection of polarized broad lines. These features, attributed to scattering of broad-line emission above the poles of the torus (e.g., Antonucci & Miller 1985), reveal the presence of an otherwise obscured BLR in many S2’s. The search for polarized broad lines has motivated many subsequent spectropolarimetric studies of S2’s (Tran et al. 1992; Young et al. 1996; Tran 2001). The optical polarization position angle (P.A.;  $\theta_v$ ) in S2’s is usually oriented perpendicular to the projected radio source axis and hence the axis of the obscuring toroidal region (Antonucci 1983; Brindle et al. 1990). This is consistent with the simple polar scattering envisaged in the unified model, because scattered light

is polarized perpendicular to the scattering plane that contains the incident rays.

In contrast,  $\theta_v$  is parallel to the radio source axis in the majority of S1’s (Antonucci 1983; Smith et al. 2002). This implies scattering in a plane perpendicular to the system principal axis, which in turn indicates a second scattering region that is present in S1’s but not observed in S2’s. Spectropolarimetric studies have shown that S1’s often exhibit distinctive structure in both  $\theta_v$  and the percentage of optical polarization ( $p_v$ ) across the broad  $H\alpha$  emission-line profile (Goodrich & Miller 1994; Martel 1996, 1998; Young et al. 1999; Smith et al. 2002). Such features are naturally produced if the line emission originates in a rotating disk (presumably the outer regions of the accretion disk itself) and is scattered in a compact region that is coplanar with the disk, and closely surrounds the BLR (Smith et al. 2005). This equatorial scattering region (ESR) is thus obscured by the torus in S2’s and has the correct geometry to account for the observed alignment of  $\theta_v$  with the radio position angle (RPA) in S1’s.

However, it is also evident that S1’s as a class exhibit a much wider range of optical polarization properties than S2’s (Smith et al. 2002, 2004). In addition to the equatorially scattered objects, about 20% exhibit null polarization, while  $\sim 25\%$  show characteristics of S2-like polar scattering. This diversity in the optical polarization properties of Seyfert nuclei can be understood if *both* polar and ESRs are present in all Seyferts. The form of the observed polarization is then determined largely by the inclination of the torus axis to the line of sight (Smith

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**Figure 1.** Refined AGN model of Smith et al. (2004) showing the two-component scattering geometry proposed to explain the optical polarization characteristics of Seyfert nuclei. The ESR is modeled as a flared disk that closely surrounds the accretion disk. The PSR is modeled as a truncated cone aligned with the axis of the circum-nuclear torus. The two regions produce orthogonal polarization. We assume that the symmetry axes of the emission disk, both the scattering regions, and the torus are co-aligned and define the principal axis of the system. The observed optical polarization depends on orientation: if the line of sight lies in region 1, we would see a null-polarization S1, in region 2 an equatorially scattered S1, in region 3 a polar-scattered S1, and in region 4 an S2.

et al. 2004). See Figure 1 for a schematic representation of this model. As inclination increases from pole-on to edge-on we first see null polarization S1’s, then S1’s dominated by equatorial scattering (where  $\theta_v$  is aligned with the radio source axis). With a further increase in inclination we see polar-scattered S1’s (with  $\theta_v$  perpendicular to the radio axis), and finally S2’s, like NGC 1068, that exhibit polarized broad lines due to polar scattering.

In this model, therefore, the polar-scattered S1’s occupy an orientation regime intermediate between unobscured S1’s and totally obscured S2’s. The direct line of sight to the nucleus passes through the torus at high latitudes and is subject to a modest amount of extinction ( $A_v \sim 1-4$  mag). The resulting attenuation of light from the ESR (within the torus) allows the orthogonally polarized flux from the extended polar scattering region (PSR; outside the torus) to dominate the net polarization. In the context of recent clumpy torus models (Nenkova et al. 2002, 2008a, 2008b; Hönig et al. 2006), an S2 or a polar-scattered S1 will be observed depending on whether or not the line of sight is intercepted by one or more dense clouds, with the probability of this occurring being a decreasing function of inclination. Unlike in S2’s, however, the relatively modest line-of-sight extinction in polar-scattered S1’s does not suppress the direct emission from the BLR.

This simple model can in principle be tested by obtaining polarimetry observations at longer wavelengths. For example, at  $2.0 \mu\text{m}$  extinction along direct lines of sight to the nucleus will be a factor of 10 less than at V, suggesting that it may be possible to detect the polarization signature of the ESR at NIR wavelengths, even though polar scattering dominates at optical wavelengths. Since the scattering geometry dictates that the polarization produced by the ESR must be orthogonal to that produced by the PSR, the presence of equatorial scattering is easily confirmed by comparing the polarization P.A. at  $2.0 \mu\text{m}$

( $\theta_{2\mu\text{m}}$ ) with that measured in the optical ( $\theta_v$ ). Furthermore, the compact ESR will only contribute to the polarization of the unresolved nucleus, whereas the more extended PSR would be expected to dominate any off-nucleus polarization.

Here we present NICMOS  $2.0 \mu\text{m}$  imaging polarimetry observations of six polar-scattered S1’s, obtained for this purpose. The high spatial resolution of *Hubble Space Telescope* (HST)/NICMOS (0.2) is desirable as it minimizes cancellation between the two orthogonal polarization states and may perhaps even resolve the two scattering regions.

The paper is organized as follows. In Section 2, we outline the sample selection and describe our observations and data reduction. Our approach to the polarimetric analysis of the data is described in Section 3 and the results are presented in Section 4. We discuss these results in the context of the two-component scattering model in Section 5 and present our conclusions in Section 6.

## 2. OBSERVATIONS AND DATA REDUCTION

The six S1’s selected for this study were drawn from the list identified by Smith et al. (2004) as showing clear spectropolarimetric signatures of polar scattering. In general, polar-scattered S1’s are characterized by a systematic increase in the degree of polarization over the optical spectrum, while the polarization P.A. is approximately constant, without the large excursions over the broad Balmer lines that are commonly seen in equatorially scattered S1’s. For the objects studied here, the range in  $p_v$  over the wavelength range  $\sim 4500-7100 \text{ \AA}$  and the value of  $\theta_v$ , averaged over the same range, are listed for each object in Table 1, along with several other properties of interest.

The observations were designed to mitigate or facilitate removal of several known NICMOS camera 2 (NIC2) defects such as residual bad pixels, latent image persistence, and the inter-pixel response functions (IPRFs). A three-point spiral dither pattern, with a point spacing of  $3''.0$  (40 pixels), was executed a total of four times through each polarizer using an exposure time of 10 s (a total of 12 pointings per polarizer). The patterns were offset from each other by  $5''.0$ . These observations sample the nucleus of each target and minimize the possibility of persistence, thoroughly sample the IPRF, and allow the detection of residual bad pixels. To sample the background, 10 s images were taken through each polarizer after a  $60''.0$  offset. To check for latent image persistence, we performed aperture photometry on individual reads in the multiaccum images. Curves of growth (count rate versus time) were constructed and found to be linear over the entire exposure. In addition, the residuals between image sections both before and after illumination by the bright point sources were checked, and found to be consistent with the generic noise characteristics of NIC2. Therefore, we find no evidence of the latent images expected to result from persistence.

All data were first passed through the `calnica` pipeline with all calibration switches turned on. Accurate polarimetric analysis requires that each individual pointing be treated separately. Therefore these data were not processed through the `calnicb` pipeline. The sky images were used to subtract the background and residual dark current. As the dithered exposures have not been processed as an association (`calnicb`), they still suffered from residual bad pixels and “grot,” i.e., pixels with reduced throughput due to particulate contamination on the detector. In these cases we used the data quality image extensions, and the default “mask-file” to create a bad pixel mask that was a combination of hot and cold pixels, and pixels affected by grot. These

**Table 1**  
Sample of Polar-scattered Seyfert 1 Galaxies

Target	Type	$v_r$ ( $\text{km s}^{-1}$ )	$\phi$ (pc)	$H\alpha/H\beta$	$p_v$ (%)	$\theta_v$ ( $^\circ$ )	RPA ( $^\circ$ )	Refs.
Fairall 51	SB(rs)b Sy1	4114	55	$5.1 \pm 0.6$	3.9–7.0	140	...	1
NGC 4593	SB(rs)b Sy1	2830	38	$3.5 \pm 0.2$	0.1–0.6	145	...	1
NGC 3227	SAB(s) pec Sy1.5	1352	18	$4.3 \pm 0.5$	0.6–1.6	125	170	1,2
Mrk 766	SB(s)a: Sy1.5	4104	55	$6.1 \pm 0.6$	2.3–3.9	90	27	3,4
Mrk 1239	E-S0 Sy1.5	5941	79	$4.7 \pm 0.8$	4.3–6.4	129	...	3
ESO 323-G077	SB(1)0 $^{\circ}$ 0 Sy1.2	4417	59	$5.9 \pm 1.7$	2.7–4.7	84	...	5

**Notes.** Properties of the optically selected sample of polar-scattered S1's. Types have been taken from NED.<sup>8</sup> Virgo-infall corrected recessional velocities ( $v_r$ ) have also been taken from NED and used to calculate the spatial scale of the *HST*+NICMOS diffraction limit ( $\phi$ ) at  $2.0 \mu\text{m}$  ( $0''.2$ ) assuming a Hubble constant of  $73 \text{ km s}^{-1} \text{ Mpc}$ . We have estimated  $H\alpha/H\beta$  flux ratios from our optical spectropolarimetry of the broad lines (and in the case of ESO 323-G077, from the spectrum published by Schmid et al. 2003). The optical polarimetry covers the wavelength range  $4500\text{--}7100 \text{ \AA}$ ; the range in percentage polarization (red-to-blue) and the average polarization position angle over this range are listed. The uncertainties on  $\theta_v$  are all  $\leq 1^\circ$ . RPA is the radio position angle. The most up-to-date references for the optical polarimetry (listed first) and radio data (listed second) are (1) Smith et al. (2004), (2) Mundell et al. (1995), (3) A. Robinson et al. (2011, in preparation), (4) Nagar et al. (1999), and (5) Schmid et al. (2003).

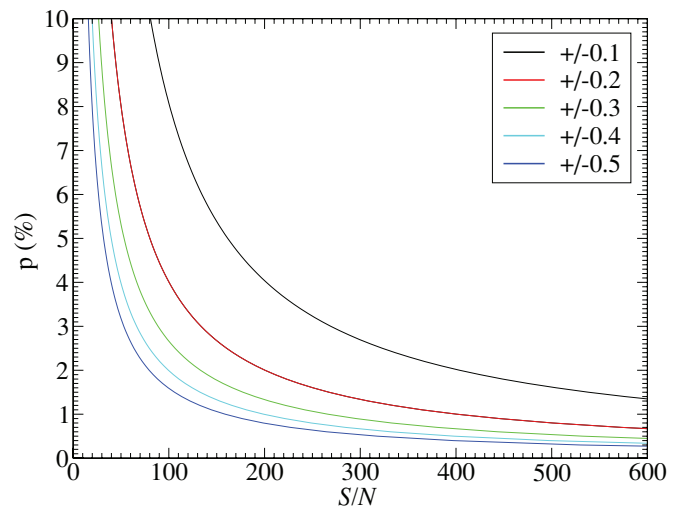
pixels were then repaired using a two-dimensional interpolation from the surrounding unaffected pixels.

### 3. POLARIMETRIC ANALYSIS

The use of NICMOS as an imaging polarimeter has been discussed previously by several authors (e.g., Hines et al. 2000; Batcheldor et al. 2006, 2009). Our polarization measurements were made using the procedures and calibrations described in Batcheldor et al. (2009). Radial profiles in the Stokes parameters  $Q$  and  $U$  were constructed for each individual pointing using the *digiphot* package within IRAF.<sup>9</sup> The average per-pixel radial profiles were then computed using an iterative  $2\sigma$  clipping procedure. In general, rejected profiles were affected by uncorrectable bad pixels and “grot,” and typically amount to 10% of the data for each source. However, in the case of ESO 323-G077 three of the twelve profiles had to be removed. The  $1\sigma$  dispersion around the average for the pointings is used to define the statistical uncertainty at each radial point.

Using the recipe of Sparks & Axon (1999), the final Stokes parameter profiles were combined to determine the percentage polarization, P.A., and associated uncertainties as functions of aperture radius. The frame orientations of the observations, which must be subtracted from the calculated polarization P.A. in order to determine  $\theta_{2\mu\text{m}}$  in the celestial reference frame, are given in Table 2 (Column 1). We define the unresolved nucleus to be the area enclosed by the second Airy maximum of the *HST*+NICMOS point-spread function (PSF), which corresponds to 7.6 pixels or  $0''.58$ . The second column of Table 2 gives the integrated signal-to-noise ratio (S/N) within this nuclear aperture for each object. Following Sparks & Axon, we have computed the detectable polarization and its associated uncertainty as a function of S/N. The polarization detectable to a given uncertainty is shown for several values of the latter in Figure 2. The limiting polarization detectable at the  $3\sigma$  level for the S/N within the nuclear apertures of our objects is listed in the third column of Table 2.

The radial profiles in  $p_{2\mu\text{m}}$  and  $\theta_{2\mu\text{m}}$  for each member of the sample are presented in Figures 3 and 4. On these diagrams, the



**Figure 2.** Theoretically achievable polarization measurements as a function of S/N. The curves correspond to increasing uncertainties in  $p$  (given in the inset). Derived from Sparks & Axon (1999).

(A color version of this figure is available in the online journal.)

**Table 2**  
Details of the Observations

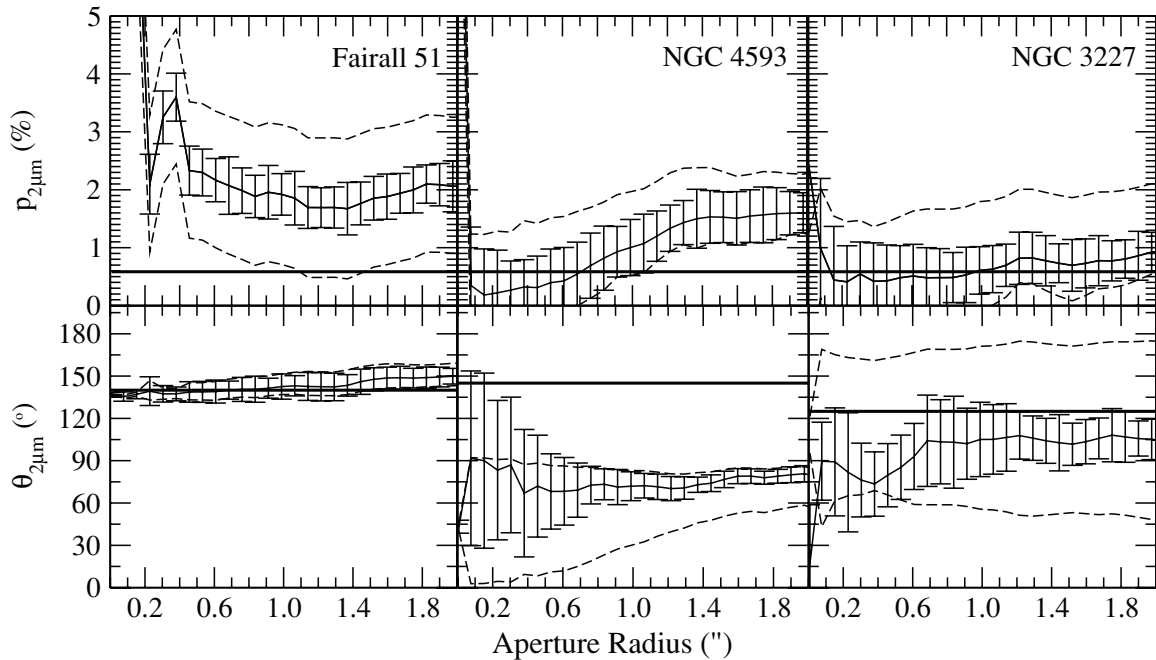
Target	Orientation ( $^\circ$ )	S/N	$p$
Fairall 51	33.4	281	1.0
NGC 4593	67.0	193	1.4
NGC 3227	75.6	106	1.9
Mrk 766	82.6	57	2.7
Mrk 1239	53.2	422	1.0
ESO 323-G077	77.0	525	0.8

**Notes.** Frame orientations for the sample (given by the NICMOS “ORIENTAT” header parameter) and the theoretically detectable polarization ( $p$ ) for the measured S/N. The S/N was determined from an aperture radius of 7.6 pixels ( $0''.58$ ), corresponding to the unresolved nucleus. The values of  $p$  are the minimum values for which a  $3\sigma$  detection is possible.

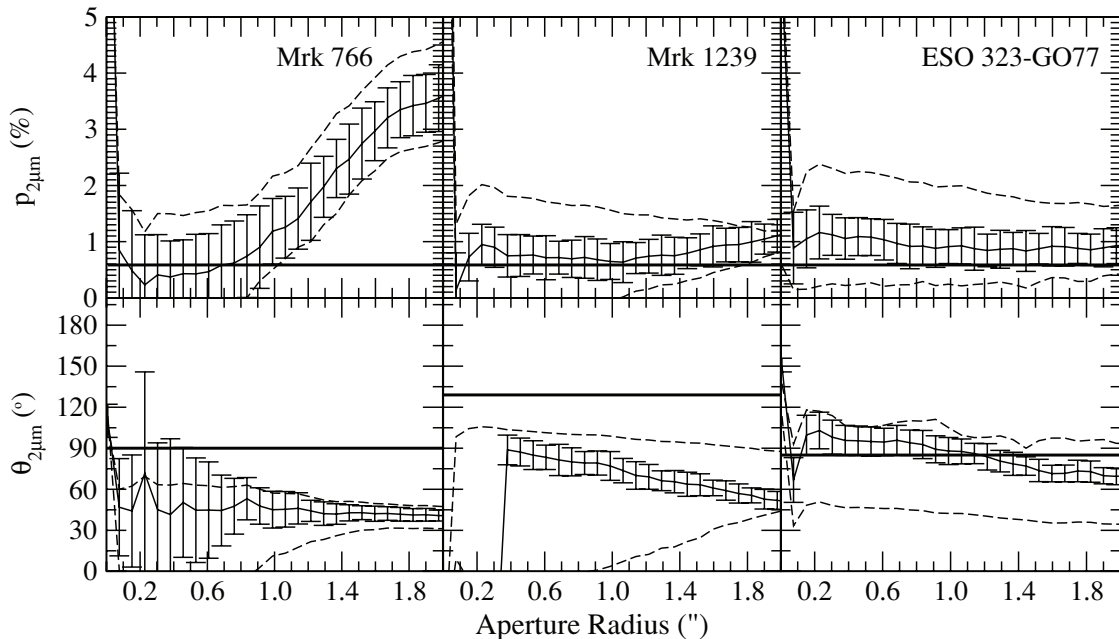
solid bars indicate the statistical uncertainty. We note that the statistical errors are correlated, as  $p_{2\mu\text{m}}$  and  $\theta_{2\mu\text{m}}$  are determined from radial integrals of the Stokes fluxes. The  $p_{2\mu\text{m}}$  panels also indicate the *upper limit* of 0.6% to the instrumental polarization of NICMOS 2, as determined by Batcheldor et al. (2009). The average optical polarization P.A. (Table 1) is shown in

<sup>8</sup> <http://nedwww.ipac.caltech.edu/>

<sup>9</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.



**Figure 3.** Radial polarization profiles at  $2.0 \mu\text{m}$ , derived from aperture polarimetry, for Fairall 51, NGC 4593, and NGC 3227. At each point, the polarization is determined from the enclosed Stokes fluxes. The error bars show the statistical uncertainties arising from photometric repeatability. The dashed lines show the possible range in values corresponding to the systematic uncertainty on the parallel transmission coefficients. Top row: radial percentage polarizations at  $2.0 \mu\text{m}$ . The solid thick line at  $p_{2 \mu\text{m}} = 0.6\%$  is the upper limit to the instrumental polarization. Bottom row:  $2.0 \mu\text{m}$  position angles. The thick solid lines mark the optical polarization position angles ( $\theta_v$ ).



**Figure 4.** Same as Figure 3 but for Mrk 766, Mrk 1239, and ESO 323-G077.

the  $\theta_{2 \mu\text{m}}$  panels. The NICMOS polarimetry is also subject to a systematic error, associated with the uncertainties in the parallel transmission coefficients  $t_k$ , which will be the same for all objects. While this can shift the values of both  $p_{2 \mu\text{m}}$  and  $\theta_{2 \mu\text{m}}$ , the radial trends will not be affected. The dashed lines in Figures 3 and 4 indicate the allowed ranges of these shifts. Table 3 lists the values  $p_{2 \mu\text{m}}$  and  $\theta_{2 \mu\text{m}}$  corresponding to aperture of radii of  $0''.58$  and  $1''.5$ .

The radial profiles contain information on the spatial variation of polarization. However, any extended source of polarization will be contaminated by the signal from the unresolved nucleus.

Therefore, we have also used the techniques outlined above to determine the polarization within an annular aperture extending to  $1''.5$ , but excluding the inner  $0''.58$  of each target. The resulting values of  $p_{2 \mu\text{m}}$  and  $\theta_{2 \mu\text{m}}$  are given in Table 4.

#### 4. RESULTS

We have detected significant polarization in all six objects, although the radial profiles exhibit diverse behavior. At first sight, the radial profiles derived from aperture polarimetry suggest that in three objects (NGC 3227, Mrk 1239, and ESO 323-G077)

**Table 3**  
The 2.0  $\mu\text{m}$  Polarization Properties of the Sample

Target	$p_{2\mu\text{m}}(\%)$ (0'.58)	$\theta_{2\mu\text{m}}(^{\circ})$ (0'.58)	$\delta\theta(^{\circ})$ (0'.58)	$p_{2\mu\text{m}}(\%)$ (1'.5)	$\theta_{2\mu\text{m}}(^{\circ})$ (1'.5)	$\delta\theta(^{\circ})$ (1'.5)
Fairall 51	$2.2 \pm 0.4$	$139 \pm 8$	$1 \pm 8$	$1.9 \pm 0.4$	$148 \pm 8$	$8 \pm 8$
NGC 4593	$0.4 \pm 0.6$	...	...	$1.5 \pm 0.4$	$77 \pm 6$	$68 \pm 6$
NGC 3227	$0.5 \pm 0.5$	...	...	$0.7 \pm 0.4$	$102 \pm 20$	$23 \pm 20$
Mrk 766	$0.6 \pm 0.7$	...	...	$2.7 \pm 0.6$	$43 \pm 5$	$47 \pm 5$
Mrk 1239	$0.7 \pm 0.4$	$83 \pm 9$	$46 \pm 9$	$0.9 \pm 0.3$	$63 \pm 8$	$66 \pm 8$
ESO 323-G077	$1.0 \pm 0.4$	$95 \pm 10$	$11 \pm 10$	$0.9 \pm 0.3$	$74 \pm 8$	$10 \pm 8$

**Notes.** Values of  $p_{2\mu\text{m}}$  and  $\theta_{2\mu\text{m}}$  for the sample. Values of  $\theta_{2\mu\text{m}}$  and  $\delta\theta$  are taken from apertures of radius 0'.58 and 1'.5 and are given in degrees in the celestial (on sky) reference frame. The values of  $\delta\theta$  give the differences between the NIR and the average optical polarization position angle (Table 1). No significant polarization was measured within the nuclear apertures of NGC 4593, NGC 3227, and Mrk 766.

$p_{2\mu\text{m}}$  is consistent with the upper bound on the instrumental polarization. However, the measured values of  $\theta_{2\mu\text{m}}$  differ significantly from object to object in the instrumental plane, indicating that the measured polarization cannot be solely instrumental in origin in all three objects. Furthermore, Mrk 1239 exhibits polarization significantly higher than the instrumental upper limit in the off-nuclear annulus, as will be discussed in more detail below. Two of our sample, Fairall 51 and Mrk 1239, are also found in NIR polarization study of Brindle et al. (1990). For Fairall 51, our results are consistent with Brindle et al.'s  $J$  &  $H$  photopolarimetry, which was obtained from a 6".0 aperture. The case of Mrk 1239 is discussed below.

Only one source, Fairall 51, exhibits radial polarization profiles consistent with a point source. Its  $p_{2\mu\text{m}}$  and  $\theta_{2\mu\text{m}}$  profiles are similar to those presented by Batcheldor et al. (2009) for polarized standard stars, which typically have large fluctuations at small radii, due to low S/N, but stabilize at constant values of  $p_{2\mu\text{m}}$  and  $\theta_{2\mu\text{m}}$  beyond the third Airy ring. In addition, no significant polarization was detected in the off-nuclear annulus for this object (Table 4). The value of  $\theta_{2\mu\text{m}}$  derived from aperture polarimetry is the same, to within  $1\sigma$ , as the average optical polarization P.A. (Tables 1 and 3).

All five of the remaining objects show evidence for extended sources of polarization. In fact, the unresolved nucleus is not significantly polarized in three of these objects—NGC 4593, NGC 3227, and Mrk 766. In NGC 4593 and Mrk 766, the  $p_{2\mu\text{m}}$  profiles show a strong increase with aperture radius once this exceeds 0'.58, resulting in significant polarizations of, respectively,  $1.5\% \pm 0.4\%$  and  $2.7\% \pm 0.6\%$  within the 1'.5 aperture (Table 3). Both objects also exhibit polarization in the off-nuclear annulus (although only at the  $\approx 2\sigma$  level in NGC 4593). However, in both cases the values of  $\theta_{2\mu\text{m}}$ , whether measured from the 1'.5 aperture or the annulus, differ widely from the optical polarization P.A. NGC 3227 yields only a marginal ( $\approx 2\sigma$ ) detection of  $p_{2\mu\text{m}}$  in the 1'.5 aperture. However, this object is significantly, albeit weakly, polarized in the off-nuclear annulus. The values of  $\theta_{2\mu\text{m}}$  measured from the aperture and annulus bracket the average optical value (Tables 3 and 4).

ESO 323-G077 is polarized at the level of  $\approx 1\%$  in both the unresolved nucleus (a  $2.5\sigma$  detection) and in the off-nuclear annulus. The values of  $\theta_{2\mu\text{m}}$  measured from the two regions are consistent with each other and also with the average optical P.A.

Finally, Mrk 1239 is unique among the objects studied here in that it exhibits strong evidence for a change in polarization state between the nucleus and the surrounding annulus. The unresolved nucleus is weakly polarized; our data yield only a  $\approx 2\sigma$  detection. However, the radial profile in  $p_{2\mu\text{m}}$  shows

**Table 4**  
Annular Polarimetry Results

Target	$p_a(\%)$	$\theta_a(^{\circ})$	$\delta\theta_{0'.58} (^{\circ})$	$\delta\theta_{1'.5} (^{\circ})$
Fairall 51	$0.2 \pm 0.4$	...	...	...
NGC 4593	$0.5 \pm 0.3$	$41 \pm 9$	...	$36 \pm 15$
NGC 3227	$0.4 \pm 0.1$	$166 \pm 7$	...	$44 \pm 27$
Mrk 766	$1.6 \pm 0.4$	$24 \pm 9$	...	$19 \pm 14$
Mrk 1239	$1.5 \pm 0.2$	$144 \pm 6$	$61 \pm 15$	$81 \pm 14$
ESO 323-G077	$0.9 \pm 0.2$	$83 \pm 8$	$12 \pm 18$	$9 \pm 16$

**Notes.** Percentage polarization ( $p_a$ ) and polarization position angle  $\theta_a$  at  $2\mu\text{m}$  for a circum-nuclear annulus extending from 0'.58 to 1'.5. The last two columns give the difference in  $\theta_{2\mu\text{m}}$  between the annular value ( $\theta_a$ ) and the aperture values for radii of 0'.58 and 1'.5, respectively.

evidence for a systematic increase to  $\approx 1\%$  beyond 1".4.  $\theta_{2\mu\text{m}}$  also varies systematically with radius, decreasing from  $\approx 80^{\circ}$  in the unresolved nucleus to  $\approx 60^{\circ}$  for radii  $\gtrsim 1'.5$ . The orientation of the polarization vector at  $2\mu\text{m}$  therefore differs by  $\approx 50^{\circ}$ – $70^{\circ}$  from the average optical value.

In the 0'.58–1'.5 annulus, however, the polarization is significantly higher, at  $1.5\% \pm 0.2\%$ , than in the nucleus and also quite closely aligned (within  $15^{\circ}$ ) with the average optical polarization (Tables 1 and 4). Mrk 1239 is the only object in the sample, for which the annular polarization has a P.A. significantly different to those measured in either the 0'.58 or 1'.5 apertures (Table 4). Perhaps more significant is the comparison with ESO 323-G077, which is the only other object in which we have detected polarization in both the unresolved nucleus and the annulus. In this object, the  $2\mu\text{m}$  polarization in both regions has the same P.A. as the optical spectrum. In Mrk 1239, on the other hand, there is a  $\geq 60^{\circ}$  change in P.A. between the nucleus and the circum-nuclear annulus, with the latter having approximately the same P.A. as measured in the optical.

The systematic change in  $\theta_{2\mu\text{m}}$  with increasing aperture radius (Figure 4) can be understood as the result of mixing of the Stokes fluxes from the unresolved nucleus and the surrounding extended source of polarization implied by the annular polarimetry. As the aperture radius increases, and encompasses the PSF, the contribution to the integrated Stokes fluxes from the extended source increases relative to that from the nucleus, causing a gradual change in  $\theta_{2\mu\text{m}}$  to angles intermediate between the intrinsic values for the two sources. In fact, in Figure 4,  $\theta_{2\mu\text{m}}$  changes toward the direction of the supplementary angle of  $\theta_a$ .

Our annular polarization measurements for Mrk 1239 are consistent with the  $J$  &  $H$  photopolarimetry of Brindle et al.

(1990). This suggests that the extended source, not the nucleus, dominates the polarization measured within the  $6''.0$  aperture used by these authors.

## 5. DISCUSSION

### 5.1. Predictions of the Unified Scattering Model

The polar-scattered S1's studied here are remarkable in that while their total flux optical spectra are typical of the general population of S1's, their polarization spectra show characteristics similar to those of "hidden broad-line" S2's. As previously outlined, these properties can be understood if polar-scattered S1's occupy an orientation regime (Figure 1) in which the direct line of sight to the nucleus follows a relatively transparent path through the torus, and is thus subject to modest visual extinction ( $A_V \sim 1\text{--}4$  mag).

In our NICMOS images, the compact ESR should contribute to the polarization only within the unresolved nucleus, whereas the PSR should dominate off-nucleus, if it is resolved. If the ESR is the dominant source of polarized flux at  $2\ \mu\text{m}$ , the nuclear point source will have a polarization P.A. perpendicular to that obtained from the optical spectropolarimetry. Conversely, we would expect any circum-nuclear polarized flux to come from the PSR and hence have a polarization vector aligned with that of the optical polarization.

### 5.2. Has the Equatorial Scattering Region Been Detected?

Our six targets exhibit a range of  $2\ \mu\text{m}$  polarization properties, indicating that the origin of the NIR polarization is more complex than envisaged in the basic two-component scattering model.

#### 5.2.1. Mrk 1239: Equatorial and Polar Scattering

This object presents the most compelling case for the detection of an ESR. The simplest interpretation of the annular polarimetry is that the ESR dominates the polarization of the unresolved nucleus, whereas at radii  $>0''.6$ , where the influence of the nuclear PSF is negligible, the polarization is dominated by the PSR. The clear detection of the ESR signature within  $0''.6$  implies that the size of this region is less than  $\sim 200$  pc, whereas the annular aperture within which the PSR dominates the measured polarization corresponds to a linear scale  $\sim 200\text{--}600$  pc. However, it should be noted that the inner radius of the annulus was chosen to exclude the nuclear PSF; there is no reason to believe it represents a physical boundary between the two regions. Indeed, we expect the ESR to be located within the torus, with a size limited by the dust sublimation radius ( $\sim 0.05$  pc for Mrk 1239; see Section 5.3.3). It is also likely that the PSR extends much further inward than 200 pc, but contributes a smaller fraction of the combined Stokes fluxes within the nuclear aperture than the ESR.

Mrk 1239 is a Narrow Line Seyfert 1 galaxy (Goodrich 1989) that has a number of remarkable properties. Its optical polarization is among the highest measured in an S1, and spectropolarimetry shows that the broad Balmer lines are redshifted in polarized flux. This indicates that the polar scattering medium is undergoing outflow in a  $\sim 1000\ \text{km s}^{-1}$  wind (Goodrich 1989; A. Robinson et al. 2011, in preparation). It also has an exceptionally steep soft X-ray spectrum, which exhibits warm absorbers (Grupe et al. 2004), and a strong NIR excess peaking at  $\sim 2\ \mu\text{m}$  (Rodríguez-Ardila & Mazzalay 2006). A comparison of spectral energy distributions leads Rodríguez-Ardila & Mazzalay to

infer that the active galactic nucleus (AGN) in Mrk 1239 is subject to an intrinsic reddening  $E(B - V) = 0.54$ , corresponding to a visual extinction  $A_V \sim 1.7$  mag. This is consistent with the Smith et al. (2004) estimate of the extinction along the direct path to the nucleus in polar-scattered S1's, and therefore it is entirely plausible that we are "seeing through" to the ESR in the NIR. The NIR excess can be attributed to blackbody emission from hot dust at a temperature  $\sim 1200$  K (Rodríguez-Ardila & Mazzalay 2006).

#### 5.2.2. NGC 4593 and Mrk 766

Two other objects, NGC 4593 and Mrk 766, also exhibit large differences ( $\delta\theta > 60^\circ$ ) between the  $\theta_v$  and  $\theta_{2\ \mu\text{m}}$  P.A.s. However, in both cases the polarization of the unresolved nucleus (within  $\sim 0''.6$ ) is consistent with zero, the integrated polarization only becoming significant at larger radii. The measured values of  $p_{2\ \mu\text{m}}$  and  $\theta_{2\ \mu\text{m}}$  must therefore be associated with an extended scattering region. In these objects, therefore, large values of  $\delta\theta$  do not imply the detection of the compact ESR. In fact, we would expect off-nuclear polarization to be due to polar scattering and hence parallel to the optical polarization. What then does account for the different polarization P.A.s in the optical and NIR? The measured polarization P.A. in either wave band could be influenced by other sources of polarization. An obvious source is dichroism due to aligned dust grains either in the host galaxy or our own. This is likely to be particularly significant in NGC 4593, which has a relatively low optical polarization (0.5%). For example, Hoffman et al. (2005) estimate that the optical polarization angle could be uncertain by up to  $90^\circ$  due to Galactic interstellar polarization (ISP) alone. Thus, we have to regard the comparison between the  $2\ \mu\text{m}$  and optical polarization P.A.s as highly uncertain in this case.

On the other hand, ISP contamination cannot similarly explain the observed large  $\delta\theta$  observed in Mrk 766, which has much higher optical polarization (2%–4%). Hoffman et al. estimate that Galactic ISP would change the optical polarization P.A. by  $<5^\circ$ . In this case, therefore, we must conclude that polarized flux arising from a different scattering geometry makes a substantial contribution to the off-nucleus NIR polarization. The nature of this scattering geometry is unclear, except that the average scattering plane must be  $\sim 45^\circ$  different from that of the region responsible for producing the optical polarization.

#### 5.2.3. Polar Scattering

In Fairall 51 and ESO 323-G077, the  $2\ \mu\text{m}$  polarization is closely aligned with the optical P.A., indicating that polar scattering dominates in the NIR. The PSR appears to be unresolved in Fairall 51, implying a linear size scale  $< 150$  pc. A simple luminosity scaling of the PSR size inferred for Mrk 1239 ( $r \propto L^{1/2}$ ) predicts that this region should be resolved in Fairall 51; the fact that it is not suggests a more compact distribution of scatterers in this object. Significant circum-nuclear polarization is detected in ESO 323-G077, indicating that the PSR is resolved. Evidence for extended polarization is also detected in NGC 3227, and we similarly attribute this to polar scattering, although the value of  $p_{2\ \mu\text{m}}$  is relatively low and  $\theta_{2\ \mu\text{m}}$  is not as clearly aligned with  $\theta_v$ . The low annular polarization is probably the result of geometrical cancellation of the polarization vectors.

### 5.3. The Complex $2\ \mu\text{m}$ Polarization Properties of Polar-scattered Seyfert 1's

Despite having similar optical polarization spectra, our small sample of six objects exhibits three different kinds of behavior at  $2\ \mu\text{m}$ . In this section, we discuss some possible causes of the complexity evident in our results.

#### 5.3.1. Spatial Resolution

Within the unresolved nucleus it is possible that both the ESR and PSR contribute to the polarized flux at  $2\ \mu\text{m}$ . The Stokes fluxes from these two sources will tend to cancel; if, for example, the polarizations are precisely orthogonal, the result will be a net polarization either parallel or perpendicular to the system axis, depending on which region produces the higher Stokes flux. The net polarized flux will be lower than would be the case if only one of the scattering regions contributes. In principle, this effect could account for the weak polarization in the unresolved nuclei of Mrk 766, NGC 4593, and NGC 3227. Similarly, in Fairall 51 and ESO 323-G077, the fact that the PSR appears to dominate the  $2\ \mu\text{m}$  polarization does not necessarily imply that the ESR is not present in these objects, simply that it produces relatively smaller Stokes fluxes at  $2\ \mu\text{m}$ .

If spatial resolution is a key factor in determining the observed polarization, we might expect the  $2\ \mu\text{m}$  polarization properties to be related to the linear scale (listed in Table 1). However, there is no evidence that this is the case, suggesting that the spatial resolution of the observations (and consequent mixing of orthogonal polarization states) is not the sole cause of the range of observed behavior. Indeed Mrk 1239, in which the two scattering regions are resolved, is the most distant object in our sample. In reality, the relative contributions of the ESR and PSR to the net polarization in the unresolved nucleus will be determined by multiple variables including the geometry and density of the scattering medium, the physical size of the PSR and, as we discuss below, the line-of-sight extinction.

#### 5.3.2. Extinction

If the amount of dust extinction along the direct line of sight to the nucleus is the dominant effect in determining whether or not the polarization signature of the ESR is actually observed in a given object, we might expect a correlation between nuclear reddening and the observed  $2\ \mu\text{m}$  polarization properties. Unfortunately, determining the nuclear reddening in AGNs is problematic (Grandi 1983). The most accessible nebular diagnostic, the Balmer decrement, does not have a well-determined intrinsic value for the physical conditions pertaining in the BLR. For example, cloud ensemble photoionization models computed by Korista & Goad (2004) indicate  $H\alpha/H\beta$  ratios in the range 3.7–4.9. On the other hand, recent empirical studies of the broad-line Balmer decrement in quasars indicate a mean value only slightly greater than the Case B recombination value (Dong et al. 2008). Within our sample, there is a fairly wide range in the broad-line  $H\alpha/H\beta$  ratio (3.5–6.1, Table 1), but there is no correlation with  $\delta\theta$ . Moreover, the uncertainties are such that there is no significant difference in  $H\alpha/H\beta$  between Mrk 1239, the object which (based on our results) we would expect to be least affected by reddening, and either Fairall 51 or ESO 323-G077, the objects we would expect to be most affected. If extinction differences are indeed responsible for the observed range in polarization behavior, then these variations are masked by the uncertainties in the measurement of the Balmer decrements, or by variations in the intrinsic broad-line Balmer decrements.

#### 5.3.3. Scattering Geometry

We must also consider the possibility that the effective scattering geometry for  $2\ \mu\text{m}$  radiation differs from that seen by optical photons. In the two-component scattering model, the ESR is located within the torus, and has a flattened, annular structure co-axial with the accretion disk. In order to produce the characteristic features of the  $H\alpha$  polarization, notably  $\theta(\lambda)$  variations across the line, it must also closely surround the  $H\alpha$  emitting region of the disk (Smith et al. 2005). The NIR emission from AGNs is believed to be dominated by thermal radiation from dust heated by the optical–UV continuum of the accretion disk, the  $2\ \mu\text{m}$  continuum coming predominantly from the hottest dust near the inner edge of the torus. It is unclear if this dust is part of the torus itself, or whether it is a distinct component. Mor et al. (2009) find that a hot blackbody component ( $T \sim 1400\ \text{K}$ ), in addition to a clumpy torus, is required to fit the IR spectral energy distributions of low-redshift quasars, with the blackbody component dominating at wavelengths  $\lesssim 4\ \mu\text{m}$ . Similarly, hot dust components have been found in several Seyfert galaxies, including Mrk 1239 (as already noted), Mrk 766, and NGC 4593 (see Table 1 in Riffel et al. 2009).

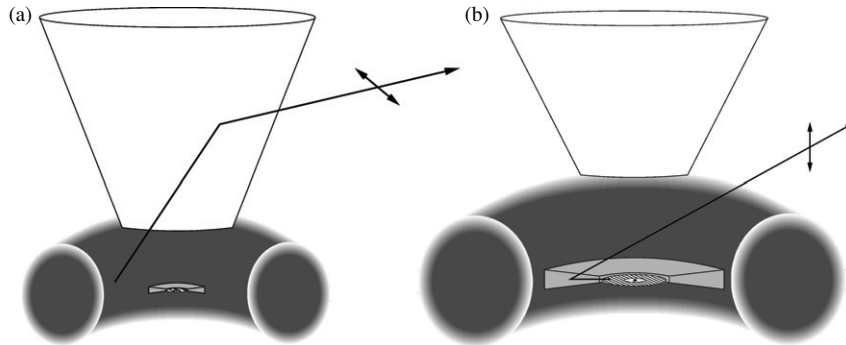
Whether or not it is part of the torus, the emitting region must be relatively compact; the radius at which dust grains have an equilibrium temperature  $T \sim 1500\ \text{K}$  is  $r_d \sim 0.4L_{45}^{0.5}$  pc, where  $L_{45}$  is the bolometric luminosity in units of  $10^{45}\ \text{erg s}^{-1}$  (Nenkova et al. 2008a; see also Barvainis 1987). If we take values of  $\lambda L_{5100\ \text{\AA}}$  measured from our spectropolarimetric data and assume the bolometric luminosity is  $\sim 9\lambda L_{5100\ \text{\AA}}$ , then  $L_{45} \sim 0.03\text{--}0.15$  and hence  $r_d \sim 80\text{--}180\ \text{ld}$ .

The BLR lies within the torus but also scales in size approximately as  $L^{0.5}$  (Kaspi et al. 2005; Bentz et al. 2009a). Using Bentz et al.'s calibration of the BLR radius–optical luminosity scaling relation, we find  $r_{\text{BLR}} \sim 10\ \text{ld}$  for our objects.

These calculations suggest, therefore, that the  $2\ \mu\text{m}$  dust-emitting region is typically a factor  $\sim 10$  larger than the BLR, and hence also the ESR, if the latter closely surrounds the BLR.<sup>10</sup> The ESR may therefore be much smaller than the hot dust NIR emission source and will intercept and scatter only a small fraction of the emitted flux. On the other hand, the PSR must extend beyond the torus and must be at least comparable in size with and probably much larger than the NIR-emitting inner region. Therefore, polarization of  $2\ \mu\text{m}$  emission due to hot dust located in or near the inner region of the torus is likely to be dominated by *polar scattering* (Figure 5(a)).

However, the outer regions of the accretion disk are also expected to emit NIR radiation. Recently, Kishimoto et al. (2008) reported that, in several quasars, the NIR continuum in polarized light exhibits an  $f_\nu \propto \nu^{1/3}$  spectrum, consistent with the characteristic long wavelength spectrum of the accretion disk. It appears that in these objects, it is the accretion disk emission, not the torus dust emission that is polarized. As the quasars they studied do not exhibit broad-line polarization, Kishimoto et al. argue that the scattering region is located well outside the NIR-emitting region of the accretion disk but *within* the radius of the BLR. A simple blackbody accretion disk model indicates that the disk will be cool enough ( $\sim 1500\ \text{K}$ ) to emit at  $2\ \mu\text{m}$  at a radius  $r_{2\ \mu\text{m}} \sim 7 \times 10^3 R_g (L/L_{\text{Edd}})^{1/3} (M_\bullet/10^7 M_\odot)^{-1/3}$ , where  $L_{\text{Edd}}$  is the Eddington luminosity,  $R_g = 2GM_\bullet/c^2$ , and

<sup>10</sup> Note, however, that in an NIR reverberation mapping study of four nearby Seyferts, including NGC 3227, Suganuma et al. (2006) find that the NIR emission region is only a factor  $\sim 2$  larger than the BLR.



**Figure 5.** (a) Polar scattering of NIR emissions from the inner edge of the torus. The solid line marks the light path. The solid line with double arrows shows the position angle of the polarization vector. In this case it is perpendicular to the principal axis due to polar scattering. Here, the ESR is a factor  $\sim 5$  smaller than the NIR-emitting region. (b) Equatorially scattered  $2 \mu\text{m}$  emission from the outer edge of the accretion disk. In this case, the position angle of the polarization vector is aligned with the principal axis; hence equatorial scattering is detected.

we have assumed a radiative efficiency of 10%. For the lower luminosity Seyferts studied here, black hole masses estimated either by reverberation mapping (Peterson et al. 2004; Bentz et al. 2009b) or by the virial method (e.g., Vestergaard & Peterson 2006; Greene & Ho 2005; see also Peterson et al. 2004) lie in the range  $M_{\bullet} \sim 0.2\text{--}4 \times 10^7 M_{\odot}$ . Therefore, given that  $L/L_{\text{Edd}} \leq 1$ , the simple disk model suggests that the  $2 \mu\text{m}$  emission comes from radii  $\lesssim 10 \text{ ld}$ , a region comparable in size with Balmer line emitting BLR. In general, therefore, the NIR-emitting region of the disk lies close to but within the ESR and accordingly we expect that  $2 \mu\text{m}$  accretion disk emission should be mainly subject to equatorial scattering, producing polarization parallel to the disk axis (and hence perpendicular to the observed optical polarization, Figure 5(b)).

These arguments suggest that the observed  $2 \mu\text{m}$  polarization may in general depend on the relative importance of scattering of torus emission by the PSR, or scattering of accretion disk emission by the ESR. As our objects are, by selection, dominated by polar scattering in the optical, and as dust emission dominates the AGN continuum at wavelengths  $\geq 2 \mu\text{m}$ , it might be expected that polar scattering will dominate the  $2 \mu\text{m}$  polarization even if the direct line of sight to the ESR is essentially transparent. This appears to be the case in Fairall 51 and ESO 323-G077. On the other hand, the two scattering regions are apparently resolved in Mrk 1239. We can plausibly attribute the polarization of the unresolved nucleus to equatorial scattering of the accretion disk emission, whereas the polarization detected off-nucleus is due to polar scattering of the hot dust emission. Thus, while the latter component might dominate the total  $2 \mu\text{m}$  flux of the unresolved nucleus, it does not contribute to the polarization *in the nucleus*.

The inner walls of the torus itself may also scatter  $2 \mu\text{m}$  emission from the disk and/or hot dust components. Scattering of light from a central point source by the inner walls of an optically thick torus can produce polarization either parallel to or perpendicular to the axis, depending on the torus opening angle and inclination (Kartje 1995; Corbett et al. 2000; Goosmann & Gaskell 2007). As the dust sublimation radius is unresolved, this polarization would only contribute to the net polarization of the unresolved nucleus. However, such a contribution is unlikely to be significant. If the NIR emission is dominated by hot dust in or near the torus opening, i.e., approximately cospatial with the scattering region, there will be a wide range in scattering angles leading to cancellation of the Stokes fluxes and a low net polarization. On the other hand, the Monte Carlo simulations of Goosmann & Gaskell (2007) indicate that the polarized flux produced by torus scattering of disk emission,

i.e., approximately a central point source, will be much smaller than the polarized fluxes produced by the PSR or ESR, for any plausible electron scattering optical depth.

#### 5.4. Wavelength Dependence of Polarization Degree

A key property of the polar-scattered Seyferts is that the optical continuum polarization increases strongly to the blue. This trend continues into the NIR, in the sense that the  $2 \mu\text{m}$  polarization of the unresolved nucleus is significantly lower, in most objects, than that measured at  $\sim 0.5 \mu\text{m}$ . The exceptions are NGC 4593 and NGC 3227, both of which have relatively low optical polarization and comparably low polarization at  $2 \mu\text{m}$ . The wavelength dependence of  $p(\lambda)$  can be attributed, at optical wavelengths, to dilution by the reddened, direct AGN (accretion disk) continuum, with a contribution from unpolarized stellar emission (which is required to account for the local increases in  $p$  over the broad emission lines; Smith et al. 2004). An old stellar population would also dilute the polarization at  $2 \mu\text{m}$ . However, it seems likely that the dominant effect in the unresolved nucleus is dilution by hot dust emission. As already noted in Section 5.3.3, blackbody components attributed to hot dust emission have been identified in several Seyfert galaxies, including Mrk 1239, Mrk 766, and NGC 4593. In the latter two cases, in particular, our aperture polarimetry reveals behavior consistent with the presence of a diluting component associated with the nucleus: the  $2 \mu\text{m}$  polarization increases significantly with radius, while the nucleus itself is weakly polarized at a level  $\lesssim 0.6\%$ , the upper limit for instrumental polarization.

We note in addition that the wavelength dependence of  $p(\lambda)$  also depends on the composition of the scattering medium. Dust scattering may well dominate in the PSR for which, if in the Rayleigh regime (grain sizes  $r \ll \lambda$ ), the scattering cross-section  $\propto \lambda^{-4}$ . Unpolarized diluting sources (e.g., starlight, accretion disk and hot dust emission) will therefore have a much greater effect in the NIR than in the optical band.

## 6. CONCLUSIONS

We have measured the nuclear polarization at  $2.0 \mu\text{m}$  in six “polar-scattered” S1 galaxies in an effort to confirm the presence of a compact ESR in these objects. This in turn would support the two-component scattering model for Seyfert galaxies. We find evidence for both equatorial and polar scattering in Mrk 1239, which exhibits the expected signatures of equatorial scattering in the unresolved nucleus, and polar scattering off-nucleus on linear scales of  $> 100 \text{ pc}$ . In this source, therefore, the compact



ESR is revealed in NIR scattered light and is clearly resolved from the PSR, which extends beyond the torus. A further implication is that the source of the *scattered*  $2\ \mu\text{m}$  emission in the unresolved nucleus is the accretion disk, as in the quasars studied by Kishimoto et al. (2008), rather than torus hot dust emission.

The remaining objects exhibit a variety of behaviors, suggesting that in general the origin of the  $2\ \mu\text{m}$  polarization is more complex than envisaged in the simple two-component scattering model. In Fairall 51 and ESO 323-G077, the nuclear polarization is evidently dominated by polar scattering, even at  $2\ \mu\text{m}$ . This cannot be taken as evidence of the *absence* of an ESR; it simply implies that the Stokes fluxes produced by this region are smaller than those produced by polar scattering. This could be the result of higher extinction to the nucleus, a smaller covering factor, or it could be that the scattered  $2\ \mu\text{m}$  radiation in these objects comes predominantly from hot dust in or near the inner part of the torus which “sees” the PSR rather than the ESR. In both NGC 4593 and Mrk 766, aperture polarimetry shows an increase in the  $2\ \mu\text{m}$  polarization with radial distance from the nucleus (where, indeed, it is consistent with zero). Conceivably, this behavior could be the result of cancellation between the orthogonal polarization components of the two scattering regions within the unresolved nucleus. However, in both cases, there is a large difference between the  $2\ \mu\text{m}$  and optical polarization P.A.s off-nucleus, where polar scattering is expected to dominate. This may not be significant for NGC 4593, in which contamination by ISP is likely to be important, but is perplexing in the case of Mrk 766, which is strongly polarized in the optical. The nucleus of NGC 3227 is also not significantly polarized at  $2\ \mu\text{m}$ . However, in this object the surrounding PSR is resolved in deeper imaging polarimetry to be presented elsewhere.

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