TWO HIGHLY POLARIZED QSOs DISCOVERED BY 2MASS

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Accepted for publication in The Astrophysical Journal Letters

ABSTRACT

We present optical observations of two remarkable new AGN discovered by the Two-Micron All Sky Survey. Both are classified as QSOs based on their optical spectra, near-IR colors, and near-IR and [O III] λ5007 luminosities, but their optical polarizations are among the highest seen for non-blazar AGN; approaching 15% for 2MASSI J151653.2+190048. The polarized light spectrum for each object exhibits broad Balmer emission lines, but lacks the narrow lines that are evident in the total light spectrum. This is most pronounced for the Type-1.5 object 2MASSI J165939.7+183436, where broad lines dominate only in polarized light. The polarization properties of these AGN suggest that dust near the nucleus at least partially obscures the AGN and that material probably intermixed with the narrow line-emitting gas scatters nuclear light into our line of sight. These QSOs illustrate the variety of highly polarized AGN that have been missed by traditional optical search techniques, and demonstrate that such objects are exposed by surveys in the near-IR.

1. INTRODUCTION

The success of orientation-based models in explaining much of the variety in the observed properties of active galactic nuclei (AGN) (see e.g., Antonucci 1993; Hines et al. 1995; Wilkes et al. 1995) has underlined the importance of obscuration located around these objects. In this class of models, a dusty torus surrounds the AGN and blocks our view of the nuclear region for high-inclination lines of sight. Not only can obscuration account for the existence of so-called “Type-2” objects dominated by narrow emission lines, but also their tendency toward higher polarization due to scattering within the narrow-line region (NLR), the presence of broad emission lines in polarized flux spectra, and their relatively large values of $L_{\text{IR}}/L_{\text{OPT}}$.

This appreciation of orientation effects has been extremely useful in establishing the equivalence (“unification”) of several apparently disparate AGN types, but it has also called attention to possible large biases in some samples of AGN (see e.g., Rowan-Robinson 1977). Traditional UV/optical survey techniques (e.g., Schmidt & Green 1983; Markarian 1967) are likely to miss AGN obscured by dust located either near the nucleus or in the body of the host galaxy. Depending on the covering factor of the obscuring material, the space density of radio-quiet AGN could be a factor of two or more greater than current surveys suggest (see e.g., Low et al. 1988; Lawrence 1991; Ho, Filippenko, & Sargent 1997).

Infrared surveys offer the advantage of being less susceptible to extinction by dust, plus they are sensitive to the more or less isotropic re-emission of the absorbed soft X-ray–optical radiation. This reprocessed component appears as a broad peak in the spectral energy distribution around 25–100 $\mu$m. The discovery of strongly polarized broad lines in “hyperluminous” infrared galaxies (HIGs: Kleinman et al. 1988; Rowan-Robinson et al. 1991; Cutri et al. 1994) found by the Infrared Astronomical Satellite proved that obscured QSOs can be detected in the IR. Unfortunately, no sensitive hard X-ray or mid-IR surveys are currently planned that would cover a large part of the sky and be suitable for determining the fraction of obscured-to-unobscured radio-quiet AGN. However, Cutri et al. (2000) have discovered a large number of previously unknown, particularly low-$z$, red AGN in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997) using a simple near-infrared color-selection criterion. That is, objects at $|b| > 30^\circ$ with $J - K_s > 2$.

In this Letter we present optical observations of two objects from the Cutri et al. (2000) sample that illustrate the variety of AGN being found by 2MASS. The high polarization induced by small-particle scattering observed for these objects confirms that near-IR surveys do indeed find obscured AGN.

2. OBSERVATIONS

High polarization was found for the AGN 2MASSI J151653.2+190048 and 2MASSI J165939.7+183436 (hereafter 2M1516 and 2M1659, respectively) during an optical polarization survey of the Cutri et al. (2000) sample (Smith et al. 2000). Basic observed properties of these two objects are provided in Table 1. The near-IR–to–optical flux ratio (as measured by $B - K_s$) for 2M1516 is near the highest value observed for the optically-selected Palomar-Green (PG) QSO sample (Smith & Green 1983; Neugebauer et al. 1987), and 2M1659 is about a magni-
tude redder. The new 2MASS AGN are similar to optically selected QSOs in that their near-IR and \([\text{O III}]\lambda 5007\) luminosities are comparable (Neugebauer et al. 1987; Boroson & Green 1992). Nevertheless, follow-up broad-band polarimetry found that the optical polarization of each object greatly exceeds the levels present in the PG catalog (Berriman et al. 1990). In fact, except for the blazar class, these two 2MASS objects are among the most highly polarized AGN known.

Optical \((\lambda \lambda 4400–8800)\) spectropolarimetry of 2M1516 and 2M1659 was obtained on UT 2000 May 9 and 1999 Oct. 13–15, respectively, using the CCD Imaging/Spectropolarimeter (Schmidt, Stockman, & Smith 1992) and Steward Observatory 2.3 m Bok reflector. The instrument configuration included a slit \(2''–3''\) wide \(\times 51''\) long plus a 600 g mm\(^{-1}\) grating to yield \(\sim 12\) Å spectral resolution. Multiple waveplate sequences on each object totaled 6720 s and 9600 s, respectively. The data are shown in Figures 1 and 2.

An additional blue spectrum of 2M1516 \((\lambda \lambda 3370–5600)\) was obtained on UT 2000 May 28 with the Boller & Chivens spectrograph and Bok reflector. A 900 s exposure was taken using a 2.5'-wide slit. These results are in excellent agreement with the flux spectrum obtained by the earlier spectropolarimetry, so the extended spectrum in Figure 1 was created by averaging the flux levels in the overlap region.

2.1. 2MASSI J151653.2+190048

The Type-1 spectrum of 2M1516 shows strong Balmer emission lines with widths FWHM \(\sim 4500\) km s\(^{-1}\) and Fe II features superposed on a fairly blue continuum. This object actually satisfies the selection criteria of the PG survey, since our spectroscopy indicates \(U – B \approx –0.5\), and \(B \approx 15.8\). Given the photometric accuracy of the PG plates and possible variability typical of QSOs, objects this close to the selection limits \((B < 16.1; U – B < –0.44)\) can be easily missed (Schmidt & Green 1983).

Spectropolarimetry confirms the high R-band polarization measured for 2M1516. In Figure 1 the continuum polarization is seen to smoothly increase from \(\sim 7\%\) at 7300 Å (rest frame) to \(\sim 15\%\) at 3700 Å. The position angle, \(\theta\), of continuum polarization is constant with wavelength. Polarization structure is apparent in the broad Balmer lines (see esp. \(\text{H}^\alpha\)), but emission from the broad-line region (BLR) is polarized to nearly the same degree and position angle as the surrounding continuum, indicating that the common polarizing mechanism is small-particle scattering. The flux from the \([\text{O III}]\) lines, however, is consistent with being unpolarized, requiring that light from the continuum source and surrounding BLR be scattered into our line of sight by material located near and/or within the NLR. The polarization structure observed in the broad emission lines suggests that the BLR is spatially resolved from the vantage point of the scattering material nearest the nucleus.

![Fig. 1.— Spectropolarimetry and spectroscopy of 2M1516. The observed quantities of polarization position angle (\(\theta\)), rotated Stokes parameter (\(q'\); this quantity avoids the statistical bias associated with \(P\), but is equivalent to \(P\) for high signal-to-noise data such as presented here), Stokes flux (\(q' \times F_{\lambda}\)), and total flux (\(F_{\lambda}\)) are displayed as a function of rest wavelength. Atmospheric O\(_2\) absorption features were removed from the \(F_{\lambda}\) and \(q' \times F_{\lambda}\) spectra through an observation of BD+28°4211 made on the same night and at a similar airmass.](image1)

![Fig. 2.— Spectropolarimetry of 2M1659. Data are displayed in the same manner as for Figure 1, though atmospheric O\(_2\) features have not been removed.](image2)
Cutri et al. (2000) classify 2M1659 a Type-1.5 AGN from their original spectroscopic observation. Narrow emission lines dominate the optical spectrum, with an [O III]λ5007 equivalent width of \( \sim 100 \) Å. The difference in contrast between the [O III] lines of 2M1516 and 2M1659 is due to the weak continuum and broad-line spectrum of the latter, not a paucity of narrow-line emission in the former, since the [O III]λ5007 luminosity measured for 2M1516 is actually \( \sim 4 \) times that of the narrow-line object. The Hα and [N II]λ6583 lines in 2M1659 are easily separated at this resolution and sit atop a broad Hα component in total flux. A weak broad-line component is also apparent at Hβ.

The optical polarization of 2M1659 averaged over the region sampled by the spectropolarimetry is \( P = 5.43\% \pm 0.06\% \) at \( \theta = 158°4' \pm 0°3' \). This is consistent with the unfiltered observation obtained 1999 Sep. 13 (Table 1), though the broad-band measurement extends \( \sim 1000 \) Å bluer. Spectropolarimetry reveals that the continuum polarization increases from \( \sim 5\% \) at 7200 Å to \( \sim 8\% \) at 3800 Å (rest), and that \( \theta \) rotates \( \sim 10° \) between these two wavelengths.

The Stokes flux spectrum \( (q' \times F_\lambda) \), where \( q' \) is the q Stokes parameter computed for a coordinate system aligned with the mean optical polarization position angle of 2M1659 is strikingly different from its total flux spectrum. The narrow emission lines which dominate the total flux are completely absent, but broad (FWHM \( \sim 6000 \) km s\(^{-1}\)) Hα and Hβ are seen. The continuum is also bluer in Stokes flux than in total flux. As with 2M1516, these properties indicate that polarization occurs through scattering by material close to, or within, the NLR.

3. DISCUSSION

The very strong optical polarizations of 2M1516 and 2M1659 are remarkable for non-blazar QSOs, but not without precedent. A few known HIGs (Hines et al. 1995; Goodrich et al. 1996; Hines et al. 1999) show broadband values which exceed that of the Type-1 source 2M1516, but all exhibit Type-2 spectra in total flux. Among Type-1 sources, the properties of 2M1659 most closely resemble Mrk 231 (Smith et al. 1995), Mrk 486 (Smith et al. 1997), and the high-polarization Seyfert galaxies studied by Goodrich & Miller (1994). Most of these objects show optical polarization that rapidly increases into the blue. In Mrk 231, \( P \) continues to increase past Mg II λ2800, reaching \( \sim 18\% \) before dilution of the scattered light by an unpolarized component, possibly hot stars, becomes important (Smith et al. 1995). Although the wavelength dependence of polarization in Mrk 231 is stronger at optical wavelengths (Schmidt & Miller 1980), the higher redshift and less-reddened spectrum of 2M1516 imply that a similar stellar component would be less significant, so its ultraviolet polarization could easily exceed 25%.

The existence of structure in \( P \) and \( \theta \) across the broad emission lines of 2M1516 is a property also shared by other polarized Type-1 AGN. Similar polarimetric signatures at Hα in Mrk 231 and Mrk 486 have been explained as the result of at least two differently-polarized emission-line components from the BLR (Goodrich & Miller 1994; Smith et al. 1995, 1997). The likelihood of multiple polarized components suggests that the scattering material must lie close to or partially within the BLR (see also Goodrich 1995).

By contrast, the strong optical polarization and high NLR/BLR flux ratio of 2M1659, traits now familiar from polarization studies of Type-2 Seyfert galaxies and HIGs, attest to an AGN partially obscured from our direct view. Such objects are important for understanding the orientation effects that are thought to unify apparently disparate classes of AGN. Past optical QSO surveys have likely been biased against finding these narrow-line objects because obscuration tends to place even low-z objects below survey limiting magnitudes and outside of survey color-selection criteria. For example, 2M1659 falls 2 magnitudes below the PG survey limit at \( B \) despite the fact that its apparent \( K \) magnitude is close to the median for PG QSOs \( (K = 12.7) \). It is consistent with the orientation-based AGN scheme that many of the likely examples of Type-2 QSOs have been discovered by either IRAS (see §1) or by near-IR surveys like 2MASS (Cutri et al. 2000). New, deep multi-color optical surveys such as the Sloan Digital Sky Survey (Gunn et al. 1998) and the Digital Palomar Observatory Sky Survey (Djorgovski et al. 1998) are conceivably sensitive to finding Type-2 AGN in specific redshift bands as high equivalent-width narrow lines migrate across filter band-passes (Djorgovski et al. 1999).

4. CONCLUSIONS

A population of obscured AGN with high optical polarization is being revealed by 2MASS. The importance of this new population is perhaps best illustrated by comparison to the 114 members of the PG sample, where the most strongly polarized is PG 1114+445 at only \( P \sim 2\% \) (Berriman et al. 1990). Like the 2MASS QSOs studied here, the emission lines of PG 1114+445 basically share the polarization of the continuum (Smith, Schmidt, & Allen 1995), so scattering of continuum and BLR light into our line of sight is also favored as the polarizing mechanism. Yet the very modest polarization of PG 1114+445 is accompanied by optical and near-IR colors \( (J - K = 1.9; B - K = 3.8) \) that are only slightly bluer than observed for 2M1516. This suggests that the optical color selection criterion chosen for the PG survey effectively marks a boundary between blue QSOs that are essentially unpolarized and redder QSOs where the scattered flux is not necessarily swamped by the direct, unpolarized light of the nucleus.

High polarization in QSOs is also associated with absorption features intrinsic to the AGN (see e.g., Schmidt & Hines 1999). In this vision of the AGN unification scheme, broad absorption-line regions arise through the ablation of high-velocity clouds off the surface of the obscuring torus, but these are visible – and a BALQSO appears – only if our line of sight to the nucleus just skims that surface (Weymann et al. 1991; Voit, Weymann, & Korista 1993). Large scattering angles for the reflected light coupled with partial obscuration of the nucleus is thought to account for the tendency of BALQSOs to be more highly polarized than for unobscured QSOs. Ultraviolet observations test the viability and constrain the geometry of these models, and the highly-polarized 2MASS AGN are an important sample in which to test these predictions. X-ray obser-
vations will also be indispensable for determining column densities and the nature of the obscuring material.

Compared with current optical samples, the 2MASS AGN sample contains many QSOs with very different optical properties, including highly polarized objects. While the obscured-to-unobscured ratio and space density of radio-quiet AGN in the local universe remain to be determined, it is already clear that 2MASS will provide much more unbiased estimates than currently exist.

We thank Frank Low for useful discussions and Dan McIntosh for obtaining a blue spectrum of 2M1516. We also thank an anonymous referee for critically reading the manuscript and for insightful comments concerning the spectral classification of 2M1659. RMC and BON acknowledge the support of the Jet Propulsion Laboratory operated by the California Institute of Technology under contract to NASA. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

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| Object                  | z     | $K_s$ | $J - K_s$ | $B - K_s$ | $M_{K}$ | $P (%)$ | $\theta (\degree)$ |
|------------------------|-------|-------|-----------|-----------|---------|---------|-------------------|
| 2MASSI J151653.2+190048 | 0.190 | 11.41 | 2.12      | 4.4       | -28.4   | 9.37    | 103.5 ± 0.3       |
| 2MASSI J165939.7+183436 | 0.171 | 12.91 | 2.17      | 5.3       | -26.6   | 6.26    | 162.4 ± 3.3       |

aPhotometric data are taken from the 2MASS Point Source Catalog.
b$H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$ assumed
cThe listed linear polarization was measured in the $R$-band ($\lambda\lambda 5800–7200$) for 2M1516 and $\lambda\lambda 3200–8900$ (unfiltered) for 2M1659 and has been corrected for statistical bias.