Spectropolarimetry and the Geometry of Type 1 Seyfert Nuclei

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Abstract

We describe the results of a detailed study of the polarization properties of the broad Hα line in Type 1 Seyfert nuclei. Our analysis of these data points to a model in which the broad Balmer lines are emitted by a rotating disk, and are scattered in two main regions – one co-planar with the disk and within the circum-nuclear torus, the other, the polar scattering region, outside the torus but aligned with its axis. The relative importance of the two sources of polarized light is largely determined by the inclination of the system axis to the line-of-sight.

1 Introduction

In the Unified Model for Seyfert galaxies, Type 1 (S1) and Type 2 (S2) Seyfert nuclei are the same type of object seen at different orientations, our direct line-of-sight to the nuclear continuum source and broad-line region (BLR) being blocked in the S2’s by a circum-nuclear torus of dusty molecular gas (e.g., Antonucci 1993). Spectropolarimetry has played an important role in establishing this picture; the detection of polarized broad-lines, attributed to scattering of broad-line emission above the poles of the torus (e.g., Antonucci & Miller 1985), having revealed an obscured BLR in many S2’s.

Since the E vector for scattered light is oriented perpendicular to the scattering plane (the plane containing the incident and scattered ray) the polarization position angle (PA) will be perpendicular to the axis of the radio source, provided that the latter is co-aligned with the torus axis and hence the scattering cone. This basic polar scattering picture broadly explains the optical polarization properties of S2 nuclei, in which the polarization PA is almost always perpendicular to the projected radio source axis (e.g., Antonucci 1983; Brindle et al. 1990).
In S1’s, by contrast, the polarization $\mathbf{E}$ vector tends to be aligned with the radio source axis (Antonucci 1983, 1984; Martel 1996). Evidently, scattered light emerging from S1’s follows a different path to that in S2’s, implying that the simplest unification model geometry including only the polar scattering ‘mirror’, is incomplete. In particular, it seems that we require an additional source of scattered light in S1’s to explain the alignment of the $\mathbf{E}$ vector with the radio axis. Our study of the optical polarization properties of S1’s has led us not only to a better understanding of their scattering geometry but has also provided an important insight into the structure of the BLR.

2 Observations and Results

Our analysis is based on spectropolarimetry of the broad H$\alpha$ line in 36 Type 1 Seyfert, obtained during a number of different runs at the Anglo-Australian and William Herschel Telescopes. The observations and results are described in detail in Smith 2002, Smith et al. 2002a. The sample as a whole displays a wide diversity in polarization properties but, excluding objects which are significantly contaminated by foreground interstellar polarization, we can identify three broad categories.

Six objects have very low measured polarizations (consistent with null polarization) and are, therefore, likely be intrinsically weakly polarized, regardless of any interstellar contamination.

The 20 intrinsically polarized objects exhibit a wide range of properties (Fig. 1). The average polarization is typically $\sim 1\%$ for both the continuum and broad Balmer lines, but ranges from $\sim 0.5$ to $\sim 5\%$. Most of these objects exhibit significant variations in the degree ($p$) and/or position angle ($\theta$) of polarization across the broad H$\alpha$ line profile. The detailed polarization structure varies considerably from object to object but it is possible to discern certain common characteristics: (i) a blue–red swing in position angle across the H$\alpha$ profile and (ii) a central depolarization in the core of the profile, flanked by polarization peaks in the wings.

A few objects exhibit quite different polarization spectra. These are characterised by a systematic increase in $p$ towards the blue end of the spectrum, with local increases associated with the broad H$\alpha$ and H$\beta$ lines. Furthermore, in contrast to most of the intrinsically polarized S1’s, there are no significant variations in $\theta$ over the broad-lines and indeed the PA is constant, to within a few degrees, over the entire observed spectral range.
These characteristics are remarkably similar to those of S2 nuclei in which polarized broad-lines have been detected. We have firmly identified 2 such objects in our sample, Fairall 51 and NGC 4593, and more tentatively, a third, Was 45. A literature search has revealed two more cases, Mrk 704 and Mrk 376 (Goodrich & Miller 1994).

Of the 10 objects for which the PA of the radio source axis is available, the average position angles of polarization are approximately parallel to the radio axis in 6 objects and approximately perpendicular in 3.

### 3 Equatorial Scattering

Among the objects whose average polarization PA is parallel to the radio axis is Mrk 6, which also has the most striking variations in $p$ and $\theta$ across the broad H$\alpha$ profile (Fig. 1). The orientation (averaged over wavelength) of the polarized light $\mathbf{E}$ vector relative to the radio source indicates that scattering takes place in a plane perpendicular to the radio axis, i.e., in the equatorial plane of the torus. The blue–red rotation in $\theta$ and the characteristic variation
in $p$ are both naturally explained if the \(\text{H}\alpha\) photons are emitted in a *rotating disk* and scattered in a co-planar ring closely surrounding the disk (Fig. 2).

The rotation in $\theta$ arises because red- and blue-shifted rays from opposite limbs of the disk subtend different scattering angles at each point in the ring. When the disk is viewed face-on, circular symmetry ensures complete cancellation of the polarization produced by any point in the ring by that of its orthogonal counterpart. However, when the disk is inclined, light scattered from points aligned with the projected minor axis of the disk is less completely polarized, due to the smaller scattering angle, than light scattered by points aligned with the projected major axis. This breaks the symmetry and leaves a net polarization with a PA rotation similar to that for points aligned with the major axis. The variation in $p$ is due to the fact that the scattering ring, being co-planar with the emitting disk, ‘sees’ a broader profile than the observers direct line-of-sight (which, in an S1, must necessarily be fairly close to the disk/torus axis). The combination of scattered and direct line emission, therefore, results in wavelength-dependent dilution of the polarized component, producing the characteristic peak–trough–peak structure in $p$ across the line profile. This ‘equatorial scattering’ model is discussed in more detail by Smith et al. 2002b.

Apart from Mrk 6 itself, 9 other objects in our sample display \(\text{H}\alpha\) polarization properties consistent with the model.

### 3.1 Implications for the Broad-Line Region

It has frequently been postulated that the low ionization broad-lines (particularly the Balmer lines) in AGN are emitted by a rotating disk, presumably the outer regions of the accretion disk (e.g., Collin-Souffrin 1987; Murray & Chiang 1997). However, the observational evidence has, hitherto, been ambiguous at best. We believe that our broad \(\text{H}\alpha\) polarization data represents the most compelling evidence yet that a significant fraction of the line emission does indeed originate in a disk. Although it is possible to conceive of other mechanisms that may explain either the PA swing or the variation in $p$ across the \(\text{H}\alpha\) broad-line profile, the only plausible emission source–scattering region geometry that can simultaneously account for both of these properties is the model outlined above. Moreover, since the amplitude of the $\theta$ rotation and precise form of the $p$ variation are sensitive to the disk–scattering ring distance, the radial extent of the disk and its inclination, detailed modelling of polarization properties and total flux profiles of the \(\text{H}\alpha\) and \(\text{H}\beta\) lines offers a unique and potentially powerful way of probing...
4 Polar Scattering

Some S1’s have polarization properties that are most readily explained by polar, not equatorial, scattering. These include the cases in which the polarization PA is perpendicular to the radio source axis and in particular, those objects, like Fairall 51 (Fig. 1), which have polarization spectra similar to those of S2 nuclei with detected polarized broad-lines.

The polar-scattering region is visible in both Type 1 and 2 Seyferts since it is located outside the circum-nuclear torus and polarized flux from this region will therefore contribute to the net polarization in all Seyfert nuclei. Polar-scattering clearly dominates in S2’s but our results suggest that when the direct view of the nuclear regions is not blocked by the torus, equatorial scattering usually dominates the observed polarization. Why is this not the case in the ‘polar-scattered’ S1’s?

In the context of the Unified Model, an appealing possibility is that they are objects in which the inclination of the system axis is such that our line-

Figure 2: Equatorial scattering of H$α$ emission from a rotating disk.
of-sight to the nucleus passes through the relatively tenuous upper layers of the torus and is subject to a moderate amount of extinction; enough to suppress polarized light from the equatorial plane of the torus, but not the broad wings of the Balmer lines. Thus, the polarization spectrum is effectively that of an S2, while the total light spectrum remains that of an S1. We estimate that a visual extinction $A_V \sim 1$ mag along the line-of-sight to the equatorial scattering region would be sufficient to allow polar scattering to dominate the observed polarization (Smith et al. 2002c). Interestingly, nuclear reddening estimates based on broad-band colours (Winkler et al. 1997) suggest that polar-scattered objects like Fairall 51, have somewhat higher nuclear extinctions than most S1’s.

5 Unification of Seyfert Polarization Properties

The ‘polar-scattered’ S1’s provide direct evidence that the scattering cone situated above the torus, which is responsible for the polarized broad-lines seen in many S2’s, is also present in S1’s. In our interpretation, the polar-scattered S1’s represent a transition state between unobscured (the majority of Type 1) and obscured (Type 2) Seyferts. It follows that all Seyfert nuclei have both equatorial and polar scattering regions located, respectively, inside and outside the torus. The latter is the scattering cone, which is co-axial with the torus (and radio) axis. The former is co-planar with, and closely surrounds, a rotating disk that emits a significant fraction of the broad Balmer lines.

Four inclination regimes, which produce quite distinct polarization signatures can be identified (Smith et al. 2002c; also http://star-www.herts.ac.uk/~jsmith/sequence2.htm). When the system is viewed almost face-on ($i \approx 0^\circ$), both the equatorial and polar scattering regions exhibit a high degree of circular symmetry and cancellation leads to null or very low polarization. At intermediate inclinations ($0 < i < 45^\circ$), there is no extinction along the direct line-of-sight to the nucleus and both scattering regions, as well as the broad-line region, are visible. In general, equatorial scattering dominates the observed polarization. When the inclination of the system axis is comparable to the torus opening angle ($i \approx 45^\circ$) the line-of-sight to the nucleus is subject to a moderate amount of extinction and polar-scattered S1s are observed. At still larger inclinations ($i > 45^\circ$), both the BLR and equatorial scattering region are completely obscured by the torus and the broad-lines are only visible in polarized light scattered from the polar scattering region.
A Seyfert Type 2 with polarized broad-lines is observed.

The range of polarization properties exhibited by Seyfert galaxies can, therefore, be broadly understood in terms of an orientation sequence based on the two-component scattering model.

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Discussion

Tim Heckman and Brian Boyle: Is the geometrical and kinematic structure you deduce from the BLR consistent with the picture that is inferred from reverberation mapping?

Mark Whittle: In addition to establishing the presence and geometry of the near and far field scattering medium, do these observations also demand a rotating disk geometry for the BLR, and if so, is that consistent with the reverberation results?

David Axon: In answer to both questions, as far as we can see, the only plausible geometry for the emission source that naturally explains, in combination with equatorial scattering, both the rotation in $\theta$ and the variation in $p$ across the broad H$\alpha$ line is that of a rotating disk. As to whether this
structure is consistent with reverberation mapping results, we would first say that while the latter generally seem to favour a gravitationally-dominated BLR, the precise structure (e.g. whether a disk or spherical cloud ensemble) is not strongly constrained. However, we are not claiming that all of the broad Hα emission comes from the disk – if, for example, a virialized cloud ensemble co-exists with a disk, the former would only contribute a constant polarization vector (because there is no velocity discrimination), which would not affect the form of the θ variation across the profile. In effect, spectropolarimetry is only sensitive to the disk component.