Chapter 6

Measurement of polarization of the broad Hα line in Arp 102B

6.1 Introduction

Light emitted by a thin disk with electron scattering opacity emerges polarized in the plane of the disk (Chandrasekhar 1960). For this reason, we know that simple thin disks with purely scattering atmospheres do not produce the quasar Big Blue Bump directly (Antonucci 1988). However, it has been proposed that sometimes the broad emission lines may arise in such a disk. In particular, Arp 102B is a broad line radio galaxy with broad double-peaked Balmer emission lines (>22,000 km/s FWZI) suggestive of an accretion disk origin. A disk seen at an inclined angle has *a Doppler brightened blue peak* and a less luminous red peak, while the whole profile is seen to be redshifted slightly by gravity. This describes well the displaced broad Hα peaks in Arp 102B (Chen, Halpern, and Filippenko 1989) at several epochs. A separate center-of-mass, lower velocity dispersion broad line region (BLR) component is needed to fit the profile, which can be seen in the Lyman alpha line profile where no broad double-peaked component appears (Halpern et al. 1996).

The energy in the Balmer lines is larger than the gravitational energy released by accretion in the region where they are produced. This led Chen and Halpern (1989) to propose a model in which an inner, optically thin but geometrically thick ion torus surrounding a black hole photoionizes a geometrically thin outer disk. The outer disk then reradiates Balmer emission lines. Local broadening or an emissivity that varies with radius is needed to fit the profile accurately. Chen and Halpern (1990) favor local broadening by electron scattering. This model can also account for the lack of a normal Big Blue Bump (since the inner regions are optically thin and weakly emitting in the UV/optical), the large Balmer decrement, and the flat-spectrum far infrared emission. There is a small class of active galaxies which have broad double-peaked Balmer lines which can be fit by the Chen and Halpern (1989) model. These galaxies often share the above properties with Arp 102B and are also characterized by low-ionization narrow lines, redshift of the very broad line centroids with respect to systemic, and large contributions of starlight to the optical continuum (Eracleous and Halpern 1994, but see Sulentic, Calvani, Marziani, and Zheng 1990).

There are some problems with this model: (1) Only 10% of broad line radio galaxies (and almost no quasars) show this type of emission line, which is surprising if most AGN harbor similar central engines. (2) The Balmer line profiles vary in some of these objects, and on at least one occasion the red peak in the Arp 102B broad Hα profile was higher than the blue (Miller and Peterson 1990; see also Gaskell 1988). However, the model has few parameters, is well motivated physically, and generally fits the line profiles well. Perhaps Arp 102B type objects occupy a unique part of parameter space in which the ion torus or other source of disk illumination can exist.

The model of Chen and Halpern (1990) makes three polarization predictions: (1) The line should be polarized at $\simeq 0.5\%$ if electron scattering is the local broadening mechanism (for the best-fit model, with inclination $i = 32°$). (2) *The polarized flux should be of equal height for the red and blue peaks for the best fit model.* The reason is that the red peak will be more polarized than the blue due to relativistic aberration. (3) The polarization angle should be in the plane of the disk (perpendicular to the axis of symmetry). The continuum polarization angle (which is not part of the Chen and Halpern model), PA=96°, is close to the angle of the line between the unresolved radio core and the inner radio axis, PA$\simeq$ 94° (see fig. 1 from Puschell et al. 1986). This is consistent with parallel alignment of optical polarization and radio axis seen in some other radio galaxies (Antonucci 1984). However, the radio "jet" curves, so the true axis of symmetry is uncertain. VLBI observations by Biermann et al. (1981) revealed no detectable radio structure at 0.4 pc resolution. Assuming that the axis of symmetry is in the direction of the inner part of the extended 6cm emission, then the polarization angle of the broad line should be nearly perpendicular to that of the continuum.

These predictions apply more generally than to just the ion-torus model. Qualitatively they just require external illumination of a disk, as invoked by many authors over the years (e.g. Rokaki et al. 1992).

6.2 Observations

We performed spectropolarimetry on the Hα line of Arp 102B to test the above three predictions. Eight hours of observations were taken on three different nights over four years with the 3m Shane reflector at Lick Observatory. The first two nights used the CCD Cassegrain Spectropolarimeter (Miller, Robinson, and Goodrich 1988) with a 600 line/mm grism blazed at 6500 Å, a TI 800x800 CCD, a dispersion of about 2.7Å/pixel, and a spectral range of about 5800-8000 Å. The third night used the spectropolarimeter Kast dual-beam spectrograph (Miller and Stone 1993) with a 1200 line/mm grism, a 1200x400 CCD, and covering a spectral range of 5917-7315 Å on the red side (where the Hα line is located) with a dispersion of 1.2 Å/pixel. The log of observations is in Table 6.1.

Table 6.1: Observation Log

Date	Exposure hours	Wavelength Range Å	Dispersion Å/pixel
October 6, 1989	2	5850-8052	2.77
June 15, 1991	2	5787-7976	2.76
June 26, 1993	4	5917-7315	1.18

A $2''$ slit was used, while the seeing varied between $1.7''-2.0''$ FWHM on our three observations. The data were flatfielded and sky subtracted, and the Q, U, and I Stokes parameters were calculated using standard VISTA procedures and additional polarization programs described in Miller, Robinson, and Goodrich (1988). We used an extraction window of 6 pixels ($\sim 4''$) to include most of the nuclear light while minimizing contamination by galactic starlight. A total of 9 sets of Q and U spectra were taken; these were then averaged to give a flux spectrum with signal to shot noise of about 700. The average integrated polarization from 5917Å to 7315Å in these individual observations is 0.40$\pm$0.05$\pm$0.09% at

PA=106±3 $\pm$ 6° (see Table 6.2, uncorrected for interstellar polarization), where the first errors are statistical and the second are the standard deviation of each observation estimated from all of the observations, which we call the total error.

Table 6.2: Comparison of polarization of individual observations averaged from 5917 to 7315 Å.

Obs.		Time min	Pol'n %	Pol'n angle degrees
1	10/6/89	40	0.44 ± 0.07	107 ± 4
2	10/6/89	40	0.46 ± 0.07	104 ± 4
3	10/6/89	40	0.31 ± 0.07	106 ± 7
4	6/15/91	60	0.45 ± 0.05	102 ± 3
5	6/15/91	60	0.32 ± 0.04	117 ± 4
6	6/26/93	60	0.38 ± 0.04	110 ± 3
7	6/26/93	60	0.35 ± 0.04	94 ± 4
8	6/26/93	60	0.50 ± 0.05	105 ± 4
9	6/26/93	60	0.60 ± 0.04	108 ± 2
avg 1-9			$0.40 \pm 0.05 \pm 0.09$	$106 \pm 3 \pm 6$

The total error in the polarization and position angle are probably due in part to different amounts of Arp 102B galaxy starlight contribution from guiding errors, seeing changes, and slit orientation changes. Most of the contribution to the total error in position angle comes from the 5th and 7th observations. However, when these are averaged together with the rest of the data, the average polarization changes very little, and thus they do not affect the conclusions of this paper.

A ten minute Keck Q observation is consistent with the Lick data and qualitatively confirms the Hα spectropolarimetry.

6.3 Results

The continuum polarization around the Hα line (5917-6400 Å and 7050-7315 Å) is 0.27±0.03% (statistical) at a PA of $96 \pm 3°$. This compares to a value of 0.1 - 1.2% and $107 - 126°$ at different epochs in a large $44''$ aperture in the data of

Puschell et al. (1986), who state that the percent polarization may have varied. Our polarization position angle is similar to the inner axis of the off-nuclear radio emission on their VLA 6cm map. Puschell et al. also state that the Milky Way interstellar polarization in the sight line to Arp 102B ($l = 77°, b = +35°$) is expected to be $< 0.1\%$. This is based on the reddening maps of Burstein and Heiles (1982) and the relation between maximum interstellar polarization and reddening (Hiltner 1956). However, a neighboring star $6\overset{\prime}{.}3$ away from the nucleus of Arp 102B was observed to have polarization P=0.16±0.01% and PA of 148±1°. This interstellar polarization almost certainly affects Arp 102B, so that Puschell et al.'s estimate was a bit optimistic.

The flux spectrum is shown in figure 6.1(b) with the fit to the broad wings from Chen and Halpern (1989). We see up to 10-15% variation in the shape of the very broad line profile between the three nights. The parameters used in the best fit were $\xi_1 = 350$, $\xi_2 = 1000$, $q = 3$, and $i = 32°$ (see Chen and Halpern 1989). As noted earlier, there is a third BLR component which is broader than the narrow line but cannot be attributed to the disk. Chen and Halpern attribute this to the "usual" broad line region clouds, which possibly reside further away from the nucleus. Correcting the data for contamination by starlight and polarization in the host galaxy interstellar medium is a tricky business and cannot be done in a definitive manner. According to Stauffer et al. (1983), more than 80% of the continuum in Arp 102B may be due to starlight, which is intrinsically unpolarized. But, the continuum polarized flux may derive from either the nuclear light or the starlight, and the nuclear light may be affected by host-galaxy interstellar polarization differently than the stellar continuum. We correct only for the polarization seen in the neighbor star in analyzing the Balmer line polarization since we know that this polarization in our galaxy must affect the Arp polarization. This does not change the variation in polarization across the line, but does change the magnitude and position angle of the polarization in the line. The rotated Stokes spectrum[1] is shown in figure 6.1(a), with the predicted spectrum shown for comparison. The position angle of the rotated Stokes spectrum plot is at 111° after the correction for the interstellar polarization. This is the average position angle in the broad line (from 6540-6660Å) which is constant within 2°.

We calculated the polarization in the broad Balmer line by subtracting (in

[1]This is essentially the polarized flux, plotted in a way that results in approximately symmetric, Gaussian errors

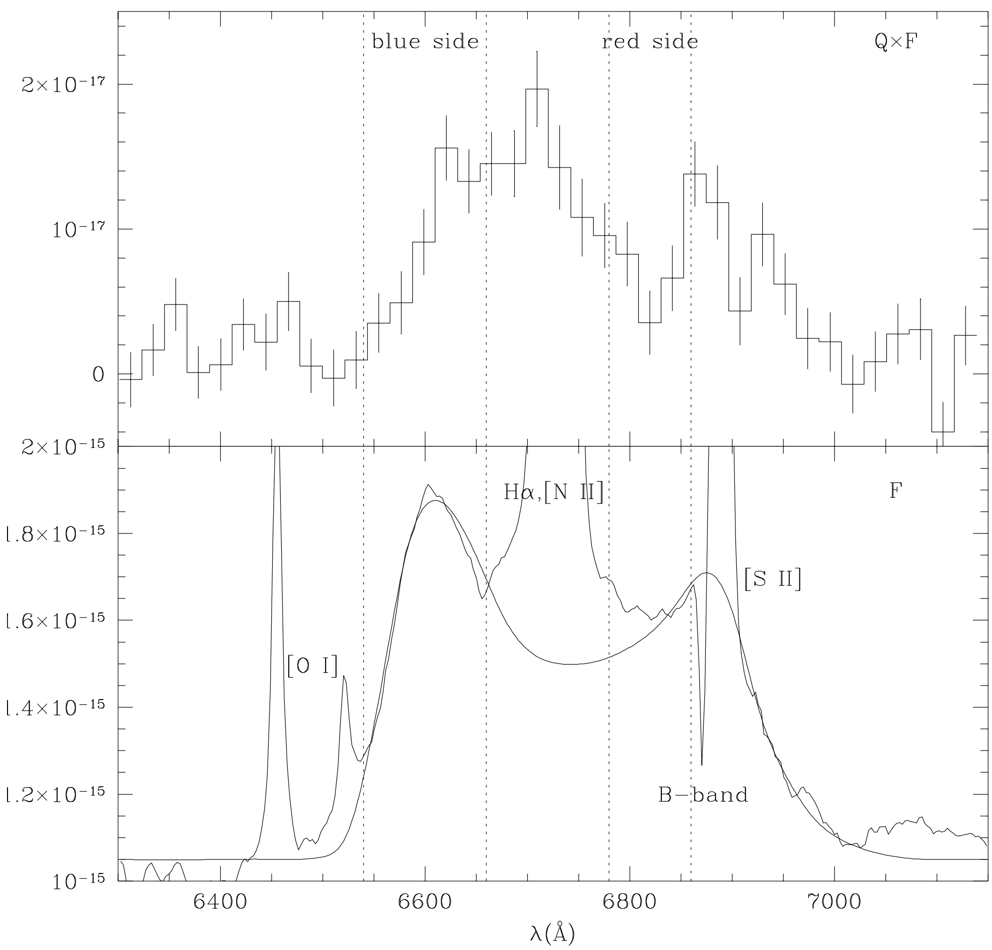

Figure 6.1: (a) Comparison of measured Stokes flux ($1-\sigma$ error bars) with model predictions (dashed line). The Stokes parameters were rotated by 111° to line up with the polarization angle in the line, which is approximately constant with wavelength in the line. The interstellar polarization estimated from the polarization of a nearby star has been subtracted. (b) Arp 102B Flux profile with model prediction for $i = 32°$. Units are erg/s/cm^2/Å

the Stokes parameters) the polarized flux of the continuum interpolated underneath the line. The results are listed in table 6.3, which shows the continuum polarization and angle before and after correction for the interstellar polarization of the neighbor star ('uncorrected' and 'corrected'), and the polarization and angle of various parts of the broad line. The polarization of the continuum on either side is $0.35 \pm 0.03\%$ at $82 \pm 3°$ (from $5917 - 6400$Å and $7050 - 7315$Å) after subtracting off the polarization of the neighbor star. Using a galaxy template instead to subtract off the continuum would not have a significant effect on the results since there are no strong stellar features under the broad Balmer line.

Table 6.3: Polarization from averaged data

Description	λ range Å	Pol'n %	Pol'n angle degrees	Comments
continuum	5917−6400 7050−7315	0.27 ± 0.03	96 ± 3	uncorrected
continuum	5917−6400 7050−7315	0.35 ± 0.03	82 ± 3	corrected
red side	6780-6860	0.89 ± 0.21	117 ± 7	corrected
blue side	6540-6660	1.12 ± 0.14	117 ± 4	corrected
high blue	6590-6660	1.49 ± 0.17	113 ± 5	corrected
total line	6540-6860	0.93 ± 0.07	111 ± 2	corrected

Recalling the predictions from section 1, we compare the polarization measurements (after subtracting off the neighbor star polarization) with the predictions from the Chen and Halpern ($i = 32°$) model:

(1) After subtracting off the continuum polarized flux interpolated under the line, the average polarization in the broad line, $0.93 \pm 0.07\%$ at $111 \pm 2°$ (see Table 6.3), is inconsistent with the prediction of 0.5%.

(2) Contrary to the predictions of the model, the polarized flux is higher in part of the blue peak than in the red peak, and it also drops too low in the far blue wing. This can be seen best by comparing the regions of the spectrum from $6540 - 6660$Å ("blue side") and $6780 - 6860$Å ("red side"), which are marked in the figure. These regions are the only parts of the broad $H\alpha$ line free of narrow lines and the "usual" broad line component, and thus are the only parts which can be directly compared to the prediction. The blue side polarization changes dramatically with wavelength (see figure 6.1(a)), contrary to the prediction, and the polarization average, $1.12 \pm 0.14\%$ at $117 \pm 4°$, is somewhat higher than on the red side, $0.89 \pm 0.21\%$ at $117 \pm 7°$. The polarization from 6590-6660Å

is 1.49±0.17% at 113±3°, which is much higher than on the red side, while *lower* polarization was predicted. In order to compare the polarization with the Chen and Halpern (1990) prediction, we need to make an assumption about the extrinsic polarization. We assume that the polarization of the continuum on either side of the Balmer line is also affecting the Balmer line, and we add this to the model prediction. This is plotted in figure 6.1(a), assuming that the polarization angle of the model is at 111°. The agreement is poor. The result would have been worse had we assumed zero extrinsic polarization for the broad line (other than that due to the Milky Way).

(3) The PA changes by $\simeq 30°$ in the line compared to the continuum, not $\simeq 90°$. Thus the line polarization is not perpendicular to the inner radio structure axis, as far as the latter can be determined from the rather odd radio morphology (Puschell et al., Fig. 1).

6.4 Discussion and conclusion

Spectropolarimetry of Arp 102B appears to be problematic for an optically thick, geometrically thin photoionized disk. It is promising that the line is polarized, but the polarization properties are inconsistent with the specific predictions. Another possible explanation for double-peaked emission lines, which has promise for the similar galaxy Pictor A (Halpern, Eracleous, Filippenko, and Chen 1996; Sulentic, Marziani, Zwitter, and Calvani 1995), is that the lines result from photoionization of a conical outflow. However, no precise predictions for polarization can be made for this model. A second suggestion in the literature is a binary black hole (e.g. Gaskell 1983) although that idea requires sub-virial BLR velocities (footnote 3 in Chen et al. 1989).

It isn't usually possible to go directly from a spectropolarimetry observation to a geometric model, but well-defined geometries and physical models can make rather unique predictions for polarization. The relativistic disk model for the broad Hα line in Arp102B leads to predictions of the percent polarization, the shape of the polarized flux, and the polarization position angle within the line, and we do not confirm any of these predictions. The displaced wings are polarized however and probably do arise in a region separate from the line core (Halpern, Eracleous, Filippenko, and Chen 1996).

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