# Chapter 8

# Conclusions

The target of this thesis was understanding the mechanism which powers the bright continuum emission of quasars. The standard thin disk paradigm faces many problems when confronted with observations, one of which is the lack of polarization of the continuum emission. The first main point of this thesis is that the low polarizations observed in QSOs cannot be used to rule out accretion disk models yet, since Faraday rotation will reduce the polarization strongly, and the observed polarization may be caused by scattering on a larger scale. Faraday depolarization is broadband and mostly featureless, and thus hard to "prove" that it is affecting the continuum polarization of QSOs. The strength and direction of the magnetic field can vary throughout the accretion disk, making it difficult to calculate its effects throughout the disk. Our calculations of polarized radiative transfer including magnetic field should be included in future attempts to model the emission regions of quasars, which are probably strongly magnetized. Numerical models of magnetohydrodynamics in accretion disks strongly suggest magnetic fields can dominate the viscous stress, and once radiative transfer is incorporated into these simulations, the formalism we have developed here for including polarization and absorption in the radiative transfer should prove useful. Observationally, the best prospects may be to look for polarization coming from the continuum in the soft X-ray region (which may be a different emission component than the UV), where Faraday rotation would be much weaker than in the optical/UV, and thus we encourage the building of X-ray detectors with polarimetric capability.

The low polarization observed in radio quiet QSOs has made it difficult to glean any information from the polarization about the continuum source. The

recent observations of high polarizations blueward of the Lyman edge cry out for an explanation, and suggest that the polarization rise may be related to the Lyman edge. Atmosphere calculations including absorption opacity show that a sharp drop, and then rise blueward of the Lyman edge is a generic feature in cool atmospheres ($T_{eff} \simeq 20,000$ K), appropriate for the most luminous objects according to theory. High polarization can only be seen for atmospheres which are somewhat edge on, so the polarization rise tends to be blueshifted beyond the wavelength where the polarization rise is seen in PG 1222+228. Also, the rise in polarization in our models is not as steep or high as seen in PG 1630+377 which rises to over 20% polarization. The high observed polarization suggests that there is strong anisotropy in the radiation field, and thus could potentially probe the geometry of the emission region. One possibility is that the polarization seen is due to a blueshifted emission edge seen in reflection. This could be caused by a strong emission edge in the inner parts of an accretion disk which is Doppler beamed towards the equatorial plane and scattered off outer regions of the disk/torus. If the disk is warped, or non-azimuthal in the outer parts, then a large scattered emission edge could be seen. If non-LTE effects cause a negative opacity in the inner regions of the accretion disk, this would cause even stronger limb brightening, and stronger polarization. The observational situation is grim since the Space Telescope Imaging Spectrometer does not have spectropolarimetric capability. Polarimetry observations have been scheduled with the Faint Object Camera (also on HST) to re-observe PG 1630+377 to confirm the high polarizations at short wavelengths. We strongly encourage ultraviolet observers to include polarization capability in their future instruments.

We have pioneered theoretical investigations into Faraday rotation in the presence of absorption opacity, and have discovered some effects which are not present when just absorption or Faraday rotation are acting. Specifically, we have found that the polarization can be increased when a magnetic field is present if the thermal source function is shallow. This effect will be difficult to detect, however, although it may be relevant for calculating the polarization of lines coming from irradiation of an accretion disk, which is a popular explanation for the broad double-peaked profiles in galaxies similar to Arp 102B. Across a line, the absorption opacity changes rapidly, while the effects of Faraday rotation are nearly constant, so this may allow us to probe the interaction of Faraday rotation and opacity in changing the polarization. If the line is coming from a region in which the magnetic field strength varies significantly, it may be

difficult to see the effects of Faraday rotation.

We have also written a fast code to compute the effects of relativity on the flux and polarization near a black hole. We have confirmed the results of Laor, Netzer, and Piran (1990) that relativity reduces the polarization significantly, although we have improved upon their disk calculations by using our more sophisticated treatment of the flux and polarization emerging from accretion disk atmospheres. The code may be useful in computing the iron line profiles observed, where a large number of line profiles must be calculated in fitting the data. It will be used in computing the flux and polarization from disk+corona models, which are currently being calculated by Omer Blaes and Chia-Ming Hsu. We also plan to use it to compute the changes in a disk spectrum during microlensing, as observed in the Einstein Cross.

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I am grateful to Roland Speith for making his code available to us.

### 8.1.5 Chapter 6

Chapter 6 was published in the same form as here in Antonucci, Hurt, and Agol (1996).

### 8.1.6 Chapter 7

Chapter 7 was published in nearly the same form as here in Agol (1996).

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## Eric Agol

**Personal**:

- born on May 13, 1970, in Hollywood, California

**Education**:

- 1994 - M.A., Physics, University of California, Santa Barbara
- 1992 - B.A., Physics and Mathematics, U. C. Berkeley

**Awards**:

- 1992 to 1994 - Regents' Fellowship, U. C. Santa Barbara
- 1992 - Phi Beta Kappa
- 1988 to 1992 - Regents' Scholarship, U. C. Berkeley
- 1988 - National Merit Scholarship
- 1988 - Elks' Club Scholarship

**Grants**:

- 1996 CalSpace grant for search for infrared microlensing in the Einstein Cross
- 1996 Infrared Satellite Observatory grant for analysis of data from search for CO absorption in Cygnus A ($62,000); PI is Robert Antonucci

**Employment**:

- 1992 to 1996 - graduate research assistant, Department of Physics, University of California, Santa Barbara
- Summer 1992 - undergraduate research assistant, Cosmic Microwave Background Explorer group, Lawrence Berkeley Laboratory

**Refereed Publications**:

1. "Polarization from Magnetized Accretion Disks: II. The Effects of Absorption Opacity on Faraday Rotation," Eric Agol, Omer Blaes, and Cristian Ionescu-Zanetti, accepted by *Monthly Notices of the Royal Astronomical Society*

2. "Polarization from Magnetized Accretion Disks in Active Galactic Nuclei," Eric Agol and Omer Blaes, 1996, *Monthly Notices of the Royal Astronomical Society*, 282, 965

3. "Polarization Near the Lyman Edge in Accretion Disk Atmosphere Models of Quasars," Omer Blaes and Eric Agol, 1996, *Astrophysical Journal Letters*, 469, L41

4. "Polarization During Binary Microlensing," Eric Agol, 1996, *Monthly Notices of the Royal Astronomical Society*, 279, 571

5. "Spectropolarimetric Test of the Relativistic Disk Model for the Broad H$\alpha$ Line of Arp 102b," Robert Antonucci, Todd Hurt, and Eric Agol, 1996, *Astrophysical Journal Letters*, 456, L25

**Proceedings**:

- "Optical/Ultraviolet Continuum Polarization of AGN Accretion Disks," Omer Blaes and Eric Agol, 1996, Proceedings of IAU Colloquium 163: Accretion Phenomena and Related Outflows, in press.

**Poster**:

- "Polarization During Caustic Crossing," 1995, Eric Agol, IAU Symposium 173, Astrophysical Applications of Gravitational Lensing

**Professional talks**:

- March 1995 - "Spectropolarimetry of Arp 102B," Caltech meeting on Spectropolarimetry of AGN

- January 1997 - "The effects of magnetic fields and absorption on the polarization of AGN accretion disk atmospheres," 189th meeting of the American Astronomical Society, Toronto, Canada

**Popular talks**:

- September 1996 - "Black Holes," 6th grade class at Solvang elementary school
- August 1996 - "Gravitational Lensing," UCSB summer science teacher curriculum development program
- March 1995 - "Gravitational Mirages," Santa Barbara Astronomy Club

**Teaching**:

- Spring 1996 - TA for Physics 210B, second quarter of graduate electrodynamics (gave two lectures)
- Fall 1995 - TA for Physics 141, undergraduate optics, and Physics 134, observational astrophysics
- Spring 1994 - TA for Astronomy 2 (gave lecture on Inflation)
- Winter 1994 - TA for Physics 133A, undergraduate astrophysics
- Fall 1993 - TA for Astronomy 1, introductory astronomy
- Fall 1992 - TA for Physics 6A, introductory physics

**Volunteer Work**:

- 1992 to 1996 - literacy tutor, Santa Barbara Rescue Mission