ABSTRACT

Name: Donna Kubik Department: Physics

Title: Strong Gravitational Lensing Systems Found in SDSS DR5

Major: Physics Degree: Master of Science

Approved by: Date:

_____ _____
Thesis Director

NORTHERN ILLINOIS UNIVERSITY

ABSTRACT

A search algorithm was implemented to select potential strong gravitational lensing systems from the Sloan Digital Sky Survey database. Visual inspection of the objects returned by the search algorithm yielded fourteen lensing candidates. A subset of these, those suitable for mass estimation via the "Einstein radius method," was selected for analysis. The redshift, z, range of the lenses is $0.38 < z < 0.49$, and the source redshift range is $0.8 < z < \sim 3$. The resultant luminosities and redshifts of the lensing galaxies were combined with the geometry and redshift estimates of the lensed galaxies to yield mass to light ratios (M/L) for systems with masses ranging from 1.28×10^{12} to 3×10^{13} $M_{\odot}$. Trends of increasing M/L with mass and radius were observed which were then compared to the literature.

NORTHERN ILLINOIS UNIVERSITY

STRONG GRAVITATIONAL LENSING SYSTEMS FOUND IN SDSS DR5

A THESIS SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE

MASTER OF SCIENCE

DEPARTMENT OF PHYSICS

BY

DONNA KUBIK

DEKALB, IL

AUGUST 2007

Certification: In accordance with departmental and Graduate School policies, this thesis is accepted in partial fulfillment of degree requirements.

_____
Thesis Director

_____
Date

ACKNOWLEDGEMENTS

I would like to thank Jim Annis for suggesting this thesis; Huan Lin, my very patient advisor, for sharing his expertise; and Dave Hedin and Steve Martin for agreeing to be on my committee, offering many helpful suggestions.

DEDICATION

To Huan Lin and Jim Annis, my astronomy mentors

TABLE OF CONTENTS

Page

LIST OF TABLES ……. x

LIST OF FIGURES ……. xii

LIST OF APPENDICES …… xvi

Chapter

1 INTRODUCTION TO GRAVITATIONAL LENSING …….. 1

1.1 Early History of Gravitational Lensing …….…. 3

1.2 Microlensing …….. 6

1.3 Weak Lensing …… 7

1.4 Strong Lensing ……... 8

1.5 What We Can Learn from Strong Lensing …….. 12

1.6 Compare Another "Natural Tool" …… 13

2 LENSING THEORY, DISTANCE MEASURES, AND PHOTOMETRIC MAGNITUDES ……. 15

2.1 Lensing Theory …… 15

2.1.1 The Lens Equation ……... 16

2.1.2 Einstein Radius …… 18

2.1.3 Lensing by a Singular Isothermal Sphere …… 19

Page

2.1.4 Why Do We See Arcs? …… …….. 20

2.1.5 Cluster Mass inside a Giant Arc …… …….…. 22

2.1.6 Conservation of Surface Brightness ……... 22

2.1.7 Magnification and Amplification ……... 23

2.2 Distance Measures ……. 26

2.2.1 Cosmological Parameters …….. 26

2.2.2 Redshift ……. 27

2.2.3 Angular Diameter Distance …….. 28

2.2.4 Luminosity Distance …… 30

2.3 Photometric Magnitude …….. 31

2.3.1 Color and the *k*-correction …….. 32

2.3.2 The AB_ν System …….. 35

2.3.3 f_ν vs. f_λ 36

2.4 Corrections for Galactic Extinction …… 39

2.5 Units …… 39

3 INTRODUCTION TO GALAXY SAMPLES ……... 42

3.1 The Lensing Galaxies ……. 43

3.1.1 Clusters ……... 44

3.2 The Lensed Galaxies …….. 44

Page

3.3 Galaxy Models …… 48

4 THE SEARCH ALGORITHM …….. 52

4.1 Motivation/Goal …….. 55

4.1.1 The BCG Catalog ……... 55

4.1.2 The LRG Catalog …… 56

4.1.3 The Arc Search Query …… 57

4.2 Details ……. 59

4.3 Results …….. 63

5 ARC IDENTIFICATION ……... 64

5.1 The Photo Pipeline …….. 64

5.2 Visual Inspection …… 65

5.2.1 Morphology …… 66

5.3 Results, Pretty Pictures ……... 71

6 USING ARCS TO FIND MASS AND MASS-TO-LIGHT RATIOS: THE EINSTEIN RADIUS METHOD 78

6.1 Mass 82

6.1.1 Einstein Radii …….. 82

6.1.2 Lens Redshifts …… 84

6.1.3 Source Redshift Estimates …….. 86

6.1.4 Mass Calculations ……... 96

6.1.5 Errors in the Mass ……... 99

Page

6.2 Light …….. 101

6.2.1 Luminosity Calculations 104

6.2.2 Errors in the Luminosity ……..… 108

6.3 Mass to Light Ratios ……..... 111

6.3.1 Errors in M/L …….....…… 111

6.3.2 Errors in Radius (Conversion from Arcsec to kpc) … 113

7 ANALYSIS OF RESULTS ……. 119

7.1 How to Measure Mass …….. 120

7.1.1 Measuring Matter Density by Cosmology …… 121

7.1.2 Detecting Matter by its Effect on the Trajectory of Mass ……. 121

7.1.3 Comparison of Mass Estimates from Dynamics to Lensing …… 126

7.2 Trends in our Data …… 127

7.2.1 M/L as f(radius) …… 128

7.2.2 M/L as f(mass) …….. 130

7.2.3 Luminosity as f(bandpass) …… 132

7.3 Comparison of Observed M/L Trends to Literature ……. 133

7.3.1 Conversion from M/L_B and M/L_V to M/L_g …….. 135

7.3.2 Comparison to Bahcall, et al. …… 138

7.3.3 Comparison to SLACS ……. 139

Page

7.3.4 Comparison to Keeton et al. ……. 143

7.3.5 Comparison to Parker et al. …….. 144

7.4 Discussion of Results …….....….... 146

7.4.1 Demonstration of Search Method ……..… 146

7.4.2 The "Einstein Radius Method" ……. 147

7.4.3 Comparison to Literature …… …. 148

REFERENCES …….…… 149

LIST OF TABLES

Table		Page
4.1	Characteristics of the DR5 imaging area ……..……	53
4.2	Number of potential BCG lenses ……..	63
4.3	Number of potential LRG lenses ……..	63
5.1	List of arc candidates selected for follow-up study ……..	72
6.1	Lensing systems chosen for analysis ……	81
6.2	Parameters required to calculate the mass ……	83
6.3	Lensing galaxy redshifts ……...	84
6.4	Lensing galaxy redshifts, redshift errors, and flags ……..	86
6.5	Redshifts from follow-up observations ……	90
6.6	Number of blue objects observed for each lensing system ……..	92
6.7	Masses and errors ……	101
6.8	Number of lensing galaxies within the Einstein radius of each lensing system ……	102
6.9	Properties of all lenses within the Einstein radius of each lensing system ……	103
6.10	Luminosities and errors in luminosity using only SDSS data (g, r, i, and z bands) …….	109
6.11	Luminosities and errors in luminosity using SDSS and follow-up data (g, r, i, and z bands) …….	110

Table Page

6.12 M/L ratios and the associated errors with SDSS data only …… 117

6.13 M/L ratios and the associated errors with SDSS and follow-up data ……. 118

7.1 Approximate mass, radius, and *M/L* for different scales …… 131

7.2 SLACS data (Treu et al. 2006, Koopmans et al. 2006) …….. 142

7.3 Empirical results Keeton et al. (1998) and average for the desired cosmology …….. 144

7.4 Comparison of masses derived from the "Einstein radius method" to those from gravlens/lensmodel ……... 147

LIST OF FIGURES

Figure		Page
1.1	White Rose with Larkspur, No. 2 by Georgia O'Keeffe 1927 ……...	1
1.2	Deflection of light by a massive compact object ……...	3
1.3	Graphical explanation of Eddington's experiment as it appeared in *Illustrated London News* of November 22, 1919. (Fernie 2005) ……..	4
1.4	Depending on the lens configuration, the observer will see multiple and strongly distorted images (giant arcs), single distorted images with elliptical shapes (arclets), or distorted images (small ellipses) ……	5
1.5	HST image of QSO 0957+561 …….	9
1.6	First observed giant gravitational arc (Soucail et al. 1987) ……...	10
1.7	Foreground galaxies in the cluster Abell 2218 distort the images of background galaxies ……	11
1.8	Evidence for maser amplification of pulsar signal (Weisberg et al. 2005) ……..	14
1.9	A schematic model of the interstellar medium (ISM) toward PSR B1641-45 showing the alignment of the pulsar, OH maser, and observer. (Weisberg et al. 2005) …….	14
2.1	Illustration of a gravitational lens system (Narayan and Bartelmann 1997) ……..	17
2.2	Arc formation ……	21
2.3	Orion Nebula magnified by an optical lens approximately 50x, 80x, and 120x ……...	24

Figure Page

2.4 Magnified images of a source lensed by a point mass (Narayan and Bartelmann 1997) …….. 24

2.5 The angular diameter distance as a function of redshift for three different spatially flat cosmologies …… 29

2.6 The luminosity distance as a function of redshift for three different spatially flat cosmologies …….. 31

2.7 Thermal radiation curves for stars of two different temperatures (4730 C and 5730 C) ……... 33

2.8 Spectra from the SDSS and the SDSS g, r, and i bandpasses …….. 34

2.9 SDSS filter system …… 35

2.10 The same spectral information shown in f_λ and f_ν ……... 38

3.1 A Lyman break galaxy (a star-forming galaxy) has an approximately flat intensity spectrum in f_υ at wavelengths longer than the Lyman limit of 91.2 nm (Shapley et al. 2006) ….. 45

3.2 Hydrogen transitions …… 45

3.3 SDSS bandpasses and composite spectrum of deep LBG spectra (Shapley et al. 2006) …… 49

3.4 Irregular galaxy model …… 50

5.1 This shows the first discovered example of an Einstein ring, discovered by Hewitt et al. (1988) using the Very Large Array (VLA) radio telescope ……. 67

5.2 HII and star-forming knots masquerading as arcs …… 68

5.3 Example of spiral arms masquerading as arcs …….. 68

5.4 Example of spiral bars masquerading as arcs ……..…… 69

Figure Page

5.5 HST image of a star-forming region of NGC 253 ……..…… 71

5.6 lrg_3_651 ……. 73

5.7 lrg_3_28 ……..…... 73

5.8 lrg_3_757 ……. 73

5.9 lrg_3_364 ……. 74

5.10 lrg_3_810 ……. 74

5.11 lrg_3_139 ……. 74

5.12 lrg_3_227 ……. 75

5.13 lrg_3_629 ……. 75

5.14 lrg_4_581 ……. 75

5.15 lrg_3_817 ……. 76

5.16 lrg_4_606 ……. 76

5.17 lrg_4_670 ……. 76

5.18 bcg_3_067 …… 77

5.19 bcg_3_109 …… 77

6.1 Image of lrg_2_227 showing a circle fit to the arc and the Einstein radius in units of arcseconds (viewed and measured using DS9) …… 79

Figure Page

6.2 Relative locations of the source S and images I^+ and I^- lensed by an SIS mass distribution M …….. 80

6.3 SDSS filters no longer straddle the 4000 Angstrom break for z>1 … 87

6.4 Galaxy models ……...…... 91

6.5 Arc colors plotted on irregular galaxy model ……...…..... 93

6.6 Calculated masses for each lensing system …….. 97

6.7 Plots of the angular diameter distance for the distance to the source, D_s, and the lens-to-source distance, D_{ds}, and the ratio of D_s/D_{ds} 98

6.8 Luminosity for each lensing system ……... 107

6.9 M/L for *g, r, i, z* as f(mass) ……. 114

6.10 M/L for *g, r, i, z* as f(Einstein radius) units in arcsec ……. 115

6.11 M/L for *g, r, i, z* as f(Einstein radius) units in kpc/h …….. 116

7.1 Methods of determining mass …… 120

7.2 Optical and x-ray image of Coma cluster …….….. 124

7.3 CMB intensity and distortion of CMB due to SZE …… 125

7.4 M/L vs. radius for four SDSS bandpasses …….…. 129

7.5 M/L vs. mass for four SDSS bandpasses ……... 130

7.6 Mass vs. radius for our 10 lensing systems …… 131

7.7 Spectrum of a G star and an elliptical galaxy ……...……...… 132

7.8 Thesis data with data from the literature …….…… 134

LIST OF APPENDICES

Appendix		Page
A	IMAGES OF THE LENSING SYSTEMS ……	152
B	GALAXY MODEL CURVES ……..	159