The Diversity of Neutron Stars: Nearby Thermally Emitting Neutron Stars and the Compact Central Objects in Supernova Remnants

by

David L. Kaplan

ISBN: 1-58112-234-9

DISSERTATION.COM

Boca Raton, Florida
USA • 2004

The Diversity of Neutron Stars: Nearby Thermally Emitting Neutron Stars and the Compact Central Objects in Supernova Remnants

Dissertation.com
Boca Raton, Florida
USA • 2004

ISBN: 1-58112-234-9

The Diversity of Neutron Stars: Nearby Thermally Emitting Neutron Stars and the Compact Central Objects in Supernova Remnants

Thesis by
David L. Kaplan

In Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California

2004

(Defended May 24, 2004)

Acknowledgements

The past five years have been very exciting and scientifically rewarding. For help on the scientific side, I would like to acknowledge my enormous debt to my advisor, Prof. Shri Kulkarni, whose quirky advice usually turns out to be correct in the long run. While he was not my official advisor, I would also like to thank Prof. Marten van Kerkwijk, whose in-depth involvement in the details of our research and stimulating conversations enabled me to get through the weeks when Shri was traveling.

Of course, I would like to thank all of my collaborators for helping and putting up with me: Jay Anderson, Dale Frail, Derek Fox, and Herman Marshall; and the hollow supernova remnant crowd: Bryan Gaensler, Eric Gotthelf, and Pat Slane.

Very little research would have been possible without the great support from the staffs of Palomar, Keck, and Las Campanas observatories. I would especially like to thank Ray Escoffier, Rich Lacasse, Karen O'Neil, and the staff at NRAO Green Bank for all of their help with the GBT Pulsar Spigot.

For making life at Caltech tolerable, I would like to thank all of the graduate students, but most significantly Edo Berger, Micol Christopher, and Bryan Jacoby. No work would have been possible at all without the great support of Patrick Shopbell, Cheryl Southard, and Anu Mahabal.

My astronomical career began as an undergraduate at Cornell University. Since it has given me so much satisfaction and happiness, I would like to thank Richard Lovelace for introducing me to the Astronomy Department, Jim Cordes (and later Gordon Stacey and Yervant Terzian) for giving me a job, Jim Condon for a fantastic internship at NRAO, and my officemates Joe Lazio (who taught me Unix), Maura McLaughlin, and Shami Chatterjee.

For supporting me through graduate school I would like to thank the Fannie and John Hertz Foundation, whose generous fellowship enabled me to pursue my research without the constant worry over funding.

Nothing at all would have been possible without my parents, Marion and Joel.

And of course Dawn Erb.

Abstract

Neutron stars are invaluable tools for exploring stellar death, the physics of ultra-dense matter, and the effects of extremely strong magnetic fields. The observed population of neutron stars is dominated by the > 1000 radio pulsars, but there are distinct sub-populations that, while fewer in number, can have significant impact on our understanding of the issues mentioned above. These populations are the nearby, isolated neutron stars discovered by *ROSAT*, and the central compact objects in supernova remnants. The studies of both of these populations have been greatly accelerated in recent years through observations with the *Chandra X-ray Observatory* and the *XMM-Newton* telescope. First, we discuss radio, optical, and X-ray observations of the nearby neutron stars aimed at determining their relation to the Galactic neutron star population and at unraveling their complex physical processes by determining the basic astronomical parameters that define the population—distances, ages, and magnetic fields—the uncertainties in which limit any attempt to derive basic physical parameters for these objects. We conclude that these sources are 10^6 year-old cooling neutron stars with magnetic fields above 10^{13} G. Second, we describe the hollow supernova remnant problem: why many of the supernova remnants in the Galaxy have no indication of central neutron stars. We have undertaken an X-ray census of neutron stars in a volume-limited sample of Galactic supernova remnants, and from it conclude that either many supernovae do not produce neutron stars contrary to expectation, or that neutron stars can have a wide range in cooling behavior that makes many sources disappear from the X-ray sky.

Contents

I The Nearby Isolated Neutron Stars **3**

1 The Parallax and Proper Motion of RX J1856.5−3754 Revisited **5**
1.1 Introduction . . . 5
1.2 Observations, Analysis & Results . . . 6
1.2.1 Relative Astrometry . . . 6
1.2.2 Registration of Epochs . . . 11
1.2.3 Absolute Astrometry . . . 14
1.2.4 Determination of Parallax and Proper Motion of RX J1856.5−3754 . . . 14
1.3 Discussion . . . 16
1.3.1 Mass & Radius . . . 16
1.3.2 Origin & Age . . . 18
1.3.3 Energetics & Nature . . . 18
1.3.4 Local Density of Neutron Stars . . . 18
1.4 Details of Analysis . . . 20
1.5 Background Sources . . . 20

2 A Probable Optical Counterpart for the Isolated Neutron Star RX J1308.6+2127 **23**
2.1 Introduction . . . 23
2.2 Observations & Data Reduction . . . 24
2.2.1 X-ray . . . 24
2.2.2 Radio . . . 25
2.2.3 Optical . . . 25
2.3 Analysis & Discussion . . . 26

3 The Optical Counterpart of the Isolated Neutron Star RX J1605.3+3249 **31**
3.1 Introduction . . . 31
3.2 Observations & Data Reduction . . . 32
3.2.1 Hubble Space Telescope Observations . . . 32
3.2.2 Keck Observations . . . 32
3.2.3 X-ray . . . 34
3.3 Analysis & Discussion . . . 35

4 X-ray Timing of the Enigmatic Neutron Star RX J0720.4−3125 **39**
4.1 Introduction . . . 39
4.2 Observations . . . 40
4.3 Timing Analysis . . . 41
4.4 Discussion . . . 41
4.5 Conclusions . . . 45

5 The Nearby Neutron Star RX J0720.4−3125 from Radio to X-rays 49
5.1 Introduction . . . 49
5.2 Optical and UV Data . . . 51
5.2.1 Observations and Analysis . . . 51
5.2.2 Spectral Fits . . . 54
5.3 X-ray Data . . . 60
5.4 Radio Observations . . . 62
5.4.1 Synthesis Imaging . . . 62
5.4.2 Pulsation Searches . . . 63
5.5 Discussion . . . 65
5.5.1 The Spectrum . . . 65
5.5.2 Radio Luminosity . . . 68
5.6 Conclusions . . . 69

6 A Re-Analysis of the Parallax of Geminga 71
6.1 Introduction . . . 71
6.2 A Parallax for Geminga? . . . 71
6.3 Observations . . . 71
6.4 New Analysis . . . 72
6.4.1 Dither Pattern . . . 72
6.4.2 Centroiding . . . 72
6.4.3 Distortion Correction . . . 72
6.4.4 Frame Registration . . . 72
6.4.5 Parallax Determination . . . 73
6.4.6 Additional Checks . . . 73
6.5 Conclusions . . . 73

7 The Nearby Isolated Neutron Stars 75
7.1 Introduction . . . 75
7.1.1 Expectations . . . 75
7.1.2 The Legacy of *ROSAT* . . . 76
7.2 Observations of Isolated Neutron Stars . . . 78
7.2.1 X-ray Spectra . . . 78
7.2.2 X-ray Timing . . . 78
7.2.3 Optical/UV Photometry & Spectroscopy . . . 81
7.2.4 Astrometry . . . 83
7.2.5 Hα Nebulae . . . 85
7.3 What Are the INSs? . . . 86
7.3.1 ISM Accretion . . . 86
7.3.2 Accretion from Fall-Back Disks . . . 86
7.3.3 Pulsar Models & Demographics . . . 88
7.4 Isolated Neutron Stars: Laboratories for Extreme Physics . . . 93
7.4.1 Neutron Stars as Probes of QCD . . . 94
7.4.2 Constraints on Cooling and Equation of State . . . 95
7.5 Conclusions . . . 98

II Neutron Stars in Supernova Remnants **101**

8 Neutron Stars in Supernova Remnants **103**

8.1 Introduction . . . 103
8.2 Outcomes of Stellar Evolution . . . 103
8.2.1 White Dwarfs . . . 104
8.2.2 Neutron Stars . . . 104
8.2.3 Black Holes . . . 104
8.2.4 No Remnant . . . 104
8.2.5 Population Rates . . . 104
8.2.6 Type Ia SNe . . . 105
8.3 Neutron Star Cooling . . . 106
8.4 Observed Neutron Stars in SNRs . . . 107
8.4.1 Radio Observations . . . 109
8.4.2 X-ray Observations . . . 111
8.5 The Hollow SNR Problem . . . 112
8.5.1 A Comprehensive Search for Central Neutron Stars in Nearby SNRs . . . 113

9 Search for an Near-IR Counterpart to the Cas A X-ray Point Source **115**

9.1 Introduction . . . 115
9.2 Observations . . . 116
9.2.1 Cas-A Central Point Source Position . . . 116
9.2.2 Optical and Near-IR Observations . . . 117
9.3 Results . . . 118
9.4 Analysis . . . 118
9.5 Discussion & Conclusions . . . 121

10 An X-ray Search for Compact Central Sources in Supernova Remnants I **123**

10.1 Introduction . . . 124
10.2 X-ray Properties of Young Neutron Stars . . . 129
10.2.1 Radio Pulsars . . . 129
10.2.2 Pulsar Wind Nebulae . . . 129
10.2.3 AXPs & SGRs . . . 132
10.2.4 Cooling Radio-Quiet Neutron Stars/Compact Central Objects . . . 132
10.3 Survey Design . . . 133
10.3.1 A Volume-Limited Sample of Shell SNRs . . . 133
10.3.2 Neutron Star Velocities . . . 133
10.4 Observations and Data Analysis . . . 135
10.4.1 *Chandra* ACIS Survey . . . 135
10.4.2 X-ray Point-Source Detection . . . 138
10.4.3 X-ray Extended-Source Detection . . . 150
10.4.4 X-ray Timing . . . 150
10.4.5 Multi-wavelength Followup & Counterpart Identification . . . 151
10.5 Results . . . 174
10.5.1 SNR G093.3+6.9 . . . 179
10.5.2 SNR G315.4−2.3 . . . 182
10.5.3 SNR G084.2−0.8 . . . 185
10.5.4 SNR G127.1+0.5 . . . 187

10.6 Limits on Central Sources . . . 189
10.6.1 Instrumental Limitations . . . 190
10.6.2 AXPs . . . 190
10.6.3 Cooling Radio-Quiet Neutron Stars . . . 193
10.6.4 Radio Pulsars . . . 193
10.6.5 Binary Systems . . . 194
10.6.6 Accreting Black Holes . . . 195
10.6.7 Type Ia Supernovae . . . 195
10.7 Conclusions . . . 195

11 An X-ray Search for Compact Central Sources in Supernova Remnants II 199
11.1 Introduction . . . 199
11.2 Supernova Remnants . . . 200
11.2.1 SNR G065.3+5.7 . . . 200
11.2.2 SNR G074.0−8.5 . . . 200
11.2.3 SNR G156.2+5.7 . . . 200
11.2.4 SNR G160.9+2.6 . . . 201
11.2.5 SNR G205.5+0.5 . . . 201
11.2.6 SNR G330.0+15.0 . . . 201
11.3 The Sample . . . 201
11.3.1 Extended Sources . . . 205
11.4 Counterpart Identification . . . 206
11.5 *Chandra* Observations . . . 211
11.5.1 Notes on *Chandra* Sources . . . 218
11.5.2 Optical and Infrared Followup . . . 222
11.5.3 Remaining Sources . . . 223
11.6 Discussion & Conclusions . . . 237

12 Optical and Infrared Observations of CCOs in Puppis A, Vela Jr., and RCW 103 241
12.1 Introduction . . . 241
12.2 Observations . . . 242
12.2.1 RX J0822−4300 . . . 243
12.2.2 SAX J0852.0−4615 . . . 243
12.2.3 1E 161348−5055 . . . 243
12.3 Discussion & Conclusions . . . 244

Bibliography 249

List of Figures

1.1	1-D position uncertainty (pixels) vs. instrumental magnitude	9
1.2	Residual positions for background sources with best-fit proper motion removed	13
1.3	Joint confidence contours for the parallax and the magnitude of the proper motion	16
1.4	Parallactic ellipse for RX J1856.5−3754	17
1.5	Color-magnitude diagram for background sources	21
1.6	Derived proper motions for the background stars and galaxies	22
2.1	Keck ESI image of the field around RX J1308.6+2127	26
2.2	*HST*/STIS image of the field around RX J1308.6+2127	27
3.1	LRIS R-band image of the field around RX J1605.3+3249	33
3.2	STIS/50CCD image of RX J1605.3+3249	34
3.3	Color-magnitude diagram of point-like source from the STIS data	35
3.4	Spectral energy distribution for source X	36
4.1	Z_1^2 periodograms	42
4.2	Period measurements for RX J0720.4−3125	43
4.3	RMS pulsed-fraction for different energy bins	44
4.4	P-$\dot{P}$ diagram	45
5.1	STIS optical image of RX J0720.4−3125	52
5.2	Optical/UV spectrum of RX J0720.4−3125	57
5.3	Optical/UV spectrum of RX J0720.4−3125	58
5.4	Broadband spectrum of RX J0720.4−3125	59
5.5	LETGS spectrum of RX J0720.4−3125	61
5.6	Count spectrum of RX J0720.4−3125 obtained with the LETGS	62
5.7	Estimates of the $3\,\sigma$ limits that can be placed on any emission lines	63
5.8	VLA maps of the field around RX J0720.4−3125	64
5.9	Brightness temperature T_B vs. wavelength	66
6.1	Difference in source positions between pairs of observations for field stars in units of σ	74
7.1	X-ray spectra of INSs	79
7.2	P-$\dot{P}$ diagram	80
7.3	*HST* images of the optical counterparts of isolated neutron stars	82
7.4	Spectral energy distribution of isolated neutron stars	83
7.5	Motion of RX J1856.5−3754	84
7.6	Proper motion of RX J0720.4−3125	85
7.7	Rest-frame transition energies for hydrogen atmospheres, as a function of magnetic field strength	89

7.8 Venn diagram illustrating the characteristics of the pulsars in Table 7.3 92
7.9 Conjectured QCD phase diagram 94
7.10 Neutron-star mass-radius relations for different equations of state 95

8.1 X-ray luminosity versus age for the neutron stars in SNRs from Table 8.2 113
8.2 X-ray-to-IR flux ratio vs. X-ray flux for confusing sources and selected neutron stars . . . 114

9.1 Images of the region around the XPS 119
9.2 Spectral energy distribution for source A 120
9.3 Spectral energy distribution for the XPS 122

10.1 Galactic distribution of SNRs from Table 10.1 134
10.2 DRAO 1.4 GHz radio image of SNR G093.3+6.9 136
10.3 MOST 833 MHz radio image of SNR G315.4−2.3 137
10.4 DRAO 1.4 GHz radio image of SNR G084.2−0.8 137
10.5 DRAO 1.4 GHz radio image of SNR G127.1+0.5 138
10.6 Smoothed ACIS-I image of SNR G093.3+6.9 139
10.7 Smoothed ACIS-I image of SNR G315.4−2.3 140
10.8 Smoothed ACIS-I image of SNR G084.2−0.8 140
10.9 Smoothed ACIS-I image of SNR G127.1+0.5 141
10.10 L-band count vs. H-band counts for SNR G093.3+6.9 146
10.11 L-band count vs. H-band counts for SNR G315.4−2.3 147
10.12 L-band count vs. H-band counts for SNR G084.2−0.8 148
10.13 L-band count vs. H-band counts for SNR G127.1+0.5 149
10.14 Background-subtracted X-ray light curves of sources in SNR G093.3+6.9 151
10.15 Background-subtracted X-ray light curve of SNR G127.1+0.5:1 152
10.16 Optical/IR images of counterparts to X-ray sources in SNR G093.3+6.9 156
10.17 Optical/IR images of counterparts to X-ray sources in SNR G093.3+6.9 (cont.) 157
10.18 Optical/IR images of counterparts to X-ray sources in SNR G093.3+6.9 (cont.) 158
10.19 Optical/IR images of counterparts to X-ray sources in SNR G315.4−2.3 159
10.20 Optical/IR images of counterparts to X-ray sources in SNR G315.4−2.3 (cont.) 160
10.21 Optical/IR images of counterparts to X-ray sources in SNR G315.4−2.3 (cont.) 161
10.22 Optical/IR images of counterparts to X-ray sources in SNR G084.2−0.8 162
10.23 Optical/IR images of counterparts to X-ray sources in SNR G084.2−0.8 (cont.) 163
10.24 Optical/IR images of counterparts to X-ray sources in SNR G084.2−0.8 (cont.) 164
10.25 Optical/IR images of counterparts to X-ray sources in SNR G127.1+0.5 165
10.26 Optical/IR images of counterparts to X-ray sources in SNR G127.1+0.5 (cont.) 166
10.27 X-ray-to-optical/IR flux ratio vs. X-ray flux for sources in SNR G093.3+6.9 171
10.28 X-ray-to-optical/IR flux ratio vs. X-ray flux for sources in SNR G315.4−2.3 172
10.29 X-ray-to-optical/IR flux ratio vs. X-ray flux for sources in SNR G084.2−0.8 173
10.30 X-ray-to-optical/IR flux ratio vs. X-ray flux for sources in SNR G084.2−0.8 174
10.31 Number density of IR sources 175
10.32 Stellar color vs. magnitude for main-sequence stars 176
10.33 Stellar color vs. magnitude for main-sequence stars 176
10.34 Stellar color vs. magnitude for main-sequence stars 177
10.35 Offsets between X-ray sources and their proposed optical/IR counterparts 177
10.36 Histogram of the offsets between X-ray sources and their proposed optical/IR counterparts 178
10.37 X-ray luminosities as a function of age for neutron stars in SNRs 192

11.1 Hardness ratios of BSC sources from Table 11.2 . . . 205
11.2 Normalized density of BSC sources in each of the SNRs from Table 11.1 . . . 207
11.3 Background count rate vs. radius for the sources in Table 11.1. . . . 208
11.4 Separations of the *ROSAT* positions and the positions of their optical counterparts . . . 211
11.5 2MASS K_s-band images of the sources in SNR G065.3+5.7 from Table 11.2. . . . 212
11.6 2MASS K_s-band images of the sources in SNR G065.3+5.7 from Table 11.2 (cont.) . . . 213
11.7 2MASS K_s-band images of the sources in SNR G065.3+5.7 from Table 11.2 (cont.) . . . 214
11.8 2MASS K_s-band images of the sources in SNR G074.0−8.5 from Table 11.2 . . . 215
11.9 2MASS K_s-band image of the source in SNR G156.2+5.7 from Table 11.2 . . . 216
11.10 2MASS K_s-band images of the sources in SNR G160.9+2.6 from Table 11.2 . . . 216
11.11 2MASS K_s-band images of the sources in SNR G205.5+0.5 from Table 11.2 . . . 217
11.12 2MASS K_s-band images of the sources in SNR G205.5+0.5 from Table 11.2 (cont.) . . . 218
11.13 2MASS K_s-band images of the sources in SNR G330.0+15.0 from Table 11.2 . . . 219
11.14 2MASS K_s-band images of the sources in SNR G330.0+15.0 from Table 11.2 (cont.) . . . 220
11.15 2MASS K_s-band images of the sources in SNR G330.0+15.0 from Table 11.2 (cont.) . . . 221
11.16 2MASS K_s-band images of the sources in SNR G330.0+15.0 from Table 11.2 (cont.) . . . 222
11.17 X-ray-to-K_s flux ratio vs. X-ray flux for sources from Table 11.2 . . . 223
11.18 2MASS K_s-band images of the sources from Table 11.4 . . . 224
11.19 2MASS K_s-band images of the sources from Table 11.4 (cont.) . . . 225
11.20 Magellan images of 1RXS J151942.8−375255 . . . 226
11.21 *Chandra* ACIS-S3 image of 1RXS J193458.1+335301 . . . 227
11.22 Radial profiles and hardness of the events for 1RXS J193458.1+335301 . . . 228
11.23 *Chandra* ACIS-S3 spectrum of 1RXS J193458.1+335301 . . . 229
11.24 Palomar images of 1RXS J193458.1+335301 . . . 230
11.25 *Chandra* ACIS-S image of the field around 1RXS J205042.9+284643 . . . 232
11.26 *Chandra* ACIS-S3 image of 1RXS J150139.6−403815 . . . 233
11.27 *Chandra* ACIS-S3 spectrum of 1RXS J150139.6−403815 . . . 234
11.28 2MASS and Magellan images of 1RXS J150139.6−403815 . . . 236
11.29 X-ray luminosities as a function of age for neutron stars in SNRs . . . 239

12.1 Optical and infrared images of RX J0822−4300 . . . 244
12.2 Optical and infrared images of SAX J0852.0−4615 . . . 245
12.3 Optical and infrared images of 1E 161348−5055 . . . 246
12.4 Color-magnitude diagram for sources within 20″ of 1E 161348−5055 . . . 247
12.5 X-ray-to-optical/IR flux ratio vs. X-ray flux for sources from the CDF/Orion studies and selected neutron stars . . . 248

List of Tables

1.1 WFPC2 Observation Summary . . . 7
1.2 Fitted Dither Positions . . . 8
1.3 Distortion Corrected (x, y) Source Positions . . . 10
1.4 Reference Sources for Astrometry . . . 12
1.5 Motion of RX J1856.5−3754 . . . 15
1.6 Implied Distances to Neutron Stars . . . 19

2.1 Summary of Optical Observations . . . 26

3.1 Summary of Optical Observations . . . 32
3.2 Summary of Optically Detected Isolated Neutron Stars . . . 37

4.1 Summary of Observations . . . 40

5.1 Summary of STIS Observations . . . 51
5.2 Source and Background Counts for STIS UV Data . . . 53
5.3 Fits to RX J0720.4−3125 Optical/UV Data with A_0 Unconstrained . . . 55
5.4 Fits to RX J0720.4−3125 Optical/UV Data with A_0 Constrained . . . 56
5.5 Summary of *Chandra* HRC-S/LETG Observations . . . 60
5.6 One and Two Blackbody Fit to the LETG Spectrum . . . 61
5.7 Summary of VLA Observations . . . 64

7.1 The Nearby Isolated Neutron Stars Detected By *ROSAT* . . . 77
7.2 Pulsar Parameters Resulting from Different Models . . . 88
7.3 Selected Rotation-Powered Pulsars . . . 99

8.1 Summary of Outcomes for Massive Stars of Solar Metallicity . . . 105
8.2 X-ray Properties of Neutron Stars in SNRs . . . 108
8.3 Classifications of Central Sources from Table 8.2 . . . 112

9.1 Cas A X-ray Observation Summary . . . 117
9.2 Cas A Optical/Near-IR Observation Summary . . . 117

10.1 SNRs Within 5 kpc . . . 127
10.2 X-ray Properties of Central Sources from Table 10.1 . . . 130
10.3 Properties of Rotation-Powered Pulsars Associated with SNRs . . . 131
10.4 X-ray Sources in SNR G093.3+6.9 . . . 143
10.5 X-ray Sources in SNR G315.4−2.3 . . . 144
10.6 X-ray Sources in SNR G084.2−0.8 . . . 145
10.7 X-ray Sources in SNR G127.1+0.5 . . . 150

10.8 Limits to Extended X-ray Emission in SNRs G093.3+6.9, G315.4−2.3, G084.2+0.8, & G127.1+0.5 . . . 151
10.9 Optical/IR Observations of SNR G093.3+6.9 . . . 154
10.10 Optical/IR Observations of SNR G315.4−2.3 . . . 155
10.11 Optical/IR Observations of SNR G084.2−0.8 . . . 155
10.12 Optical/IR Observations of SNR G127.1+0.5 . . . 164
10.13 Optical/IR Matches to X-ray Sources in SNR G093.3+6.9 . . . 168
10.14 Optical/IR Matches to X-ray Sources in SNR G315.4−2.3 . . . 169
10.15 Optical/IR Matches to X-ray Sources in SNR G084.2−0.8 . . . 170
10.16 Optical/IR Matches to X-ray Sources in SNR G127.1+0.5 . . . 173
10.17 Classifications of X-ray Sources in SNRs G093.3+6.9, G315.4−2.3, G084.2+0.8, & G127.1+0.5 179
10.18 Limits on Central Sources in SNRs G093.3+6.9, G315.4−2.3, G084.2+0.8, & G127.1+0.5 . 191

11.1 Large SNRs . . . 202
11.2 *ROSAT* Point Sources and Stellar Counterparts . . . 203
11.3 Identification of *ROSAT* Sources . . . 209
11.4 Log of *Chandra* Observations . . . 214
11.5 Log of Optical/IR Observations . . . 226
11.6 Properties of Optical Sources in Figure 11.28 . . . 235

12.1 Optical and Infrared Observations of CCOs . . . 242

We learn wisdom from failure much more than from success. We often discover what will do by finding out what will not do; and probably he who never made a mistake never made a discovery.

— Samuel Smiles (*Self-Help*)

I have found you an argument; I am not obliged to find you an understanding.

— Samuel Johnson

Part I

The Nearby Isolated Neutron Stars

Chapter 1

The Parallax and Proper Motion of RX J1856.5−3754 Revisited†

D. L. Kaplan[a], M. H. van Kerkwijk[b‡], & J. Anderson[c*]

[a]Department of Astronomy, 105-24 California Institute of Technology, Pasadena, CA 91125, USA

[b]Sterrenkundig Instituut, Universiteit Utrecht, Postbus 80000, 3508 TA Utrecht, The Netherlands

[c]Astronomy Department, University of California, Berkeley, CA 94720-3411, USA

Abstract

RX J1856.5−3754, a bright soft X-ray source believed to be the nearest thermally emitting neutron star, has commanded and continues to command intense interest from X-ray missions. One of the main goals is to determine the radius of this neutron star. An integral part of the determination is an accurate parallax. Walter (2001) analyzed *Hubble Space Telescope* (*HST*) data and derived a parallax, $\pi = 16.5 \pm 2.3$ mas. Combining this distance with the angular radius derived from blackbody fits to observations of RX J1856.5−3754 with *ROSAT*, *EUVE*, *HST*, Pons et al. (2002a) derived an observed radius ("radiation radius"), $R_\infty = 7$ km. This value is smaller than the radii calculated from all proposed equations-of-state (EOS) of dense baryonic matter (Haensel 2001). Here, we have analyzed the same *HST* data and find $\pi = 7 \pm 2$ mas. We have verified our result using a number of different, independent techniques, and find the result to be robust. The implied radius of RX J1856.5−3754 is $R_\infty = 15 \pm 6$ km, falling squarely in the range of radii, 12–16 km, expected from calculations of neutron star structure for different equations of state. The new distance also implies a smaller age for RX J1856.5−3754 of 0.4 Myr, based on its association with the Upper Sco OB association.

1.1 Introduction

The *ROSAT* all-sky survey identified six neutron stars that are radio-quiet but bright in the soft X-ray band. These sources, unlike the well-studied radio pulsars, lack significant nonthermal emission and are thus excellent candidates for X-ray spectroscopic studies of the atmospheres of neutron stars (for reviews, see Mereghetti 2001; Treves et al. 2000).

†A version of this chapter was published in *The Astrophysical Journal*, vol. 571, 447–457.

‡Current address: Department of Astronomy and Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada.

*Current address: Department of Physics and Astronomy, Rice University, Houston, TX 77251, USA