An Optical Study of the LMC X-1 Black Hole Binary System

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LMC X-1 is an x-ray emitting compact object in a binary system with an O7 star. Analysis of the secondary stars spectrum gave a rotational velocity of 140 ± 5 km/s. A radius of 11.54 ± 0.28 $R_{\odot}$ was derived from photometry. Modeling of the radial velocity curve and light curves gave values of 3.98 ± 0.19 $M_{\odot}$ for the black hole.

Introduction

LMC X-1 is an x-ray source discovered in 1971 by the *Uhuru* x-ray satellite. It is a strong, slightly variable, but never eclipsing source. It is now known that it is in a binary system with a giant O-type star. Mass exchange in this system occurs via stellar wind from the giant to the compact object. As the mass fall into the compact object gravitation potential is converted into x-ray emission. The system is surrounded by a He II nebula most likely being ionized by the x-ray emission.

Observations and Reduction

The data I used for this study were both acquired and partially reduced by collogues before loaned to me by Dr. Orosz. Spectra were taken between 20^{th} and 25^{th} of January 2005 at Las Campanas Observatory using the Magellan Inamori Kyocera Echelle spectrograph on the 6.5m Clay telescope. The spectra was taken in two wavelengths regions: the "blue" being 3745-4900 Å and "red" at 5750-7200Å. We have 30 LMC spectra, and the spectra of bright O-type stars for comparison. The radial velocities of the LMC X-1 secondary were measured using fxcor in IRAF. Then the spectra were Doppler shifted to zero velocity, added, and normalized using IRAF in order to produce high signal to noise spectrum to model.

Photometric images were taken between January and March of 2007 at CTIO using the 1.3m SMARTS telescope. Standard image fields were taken in *BVRI* while the science images were taken in the *B* and *V* bands.

Analysis

Spectra

Visual analysis of the spectra showed that there was a signifigant amount of vertical artifacts due to the merging of the echelle orders in the creation of the larger spectra. This made it difficult to identify useful spectral lines to model. After an extensive visual search of the spectra of bright O-type comparison stars, we decided on six spectral lines with which to model; 3780-3810, 3820-3845, 4086-4116, 4182-4215, 5800-5890, and 7059-7086 Å. Models were created using the rotin3.f code of Hubeny which creates a model spectrum. We could then use a program called checkfitspect.f that would compare the created model to the data and output a χ^2 value. This process was automated for the specific spectral ranges with a code I wrote called mkspect.f. The model grid used for this analysis was the OSTAR 2002 grid of Lanz-Hubeny. This decision was based on previous study by Cowley et. al. (1994), which identified LMC X-1's optical companion as an O7 III. Results varied for the fits of temperature and gravity but a good fit for the rotational velocity was found consistently between spectrum at 140 km/s (Fig 1.).

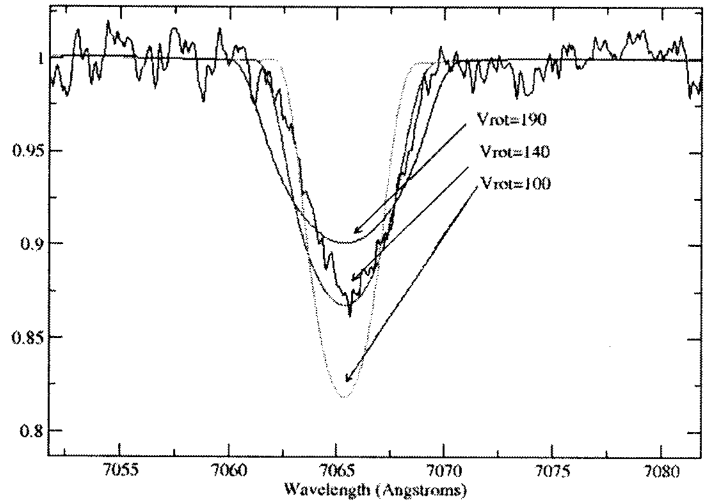

Figure 1. Model Fit to Spectrum

Photometry

Absolute photometry of LMC X-1 was done using only images with multiple standards taken the same night. The standards used were Landolt fields RU149, PG1657, and PG1047. Aperture photometry was done IRAF. The transformation to the standard system was done using tasks in the photcal package.

For the LMC X-1 fields we used all images, aligned them, and used DAOPHOT II for the time series photometry thinking it would be a better algorithm for the more crowded star field. The output of DAOPHOT II magnitudes were then corrected using the previously calculated offset.

From the photometry results we were able to build calibrated light curves which we can model, and we were able to calculate an approximate radius of the stellar companion. Making some assumptions about distance, extinctions, and a bolometric correction factor we got radius value of 11.23 ± 0.44 solar radii.

Eclipsing Light Curve Code

The ELC is an all in one modeling program that will take values independently found above along with some input ranges to find the best model fit for the radial velocity curve and light curve created previous. Genetic ELC was run with the input parameter ranges given in Table 1 with the results listed to the side. The data and best fit models are show in Figures 2 - 4.

ELC Parameters	Range	Result
Star Radius ($R_\odot$)	9. - 14.	11.54 ± .28
Inclination (Deg.)	35. - 80.	66.2 ± 3.0
Radial Velocity (km/s)	50. - 80.	69.95 ± 0.95
Period (days)	3.9 - 3.9140	3.90947 ± 0.00010
Star Temperature (K)	34000. - 38000.	36689 ± 2800
Star Mass ($M_\odot$)	5. - 45.	14.71 ± 0.83
Black Hole Mass ($M_\odot$)	*not input parameter*	3.98 ± 0.19

Table 1. ELC Constraints and Results

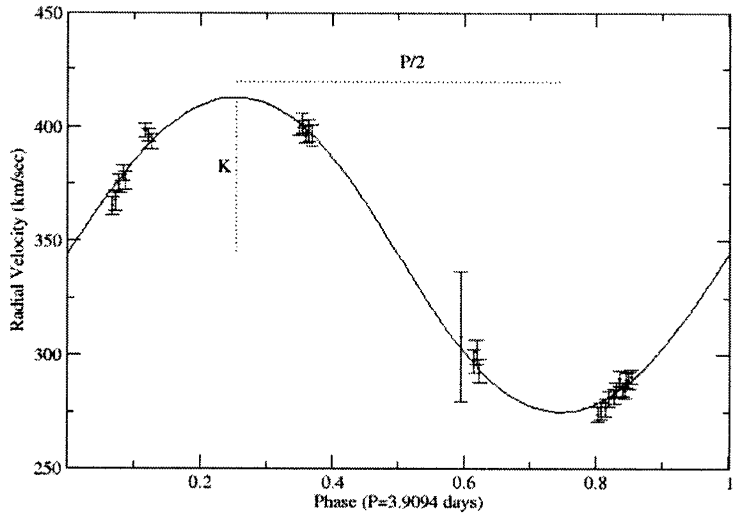

Figure 2. Radial Velocity and ELC model

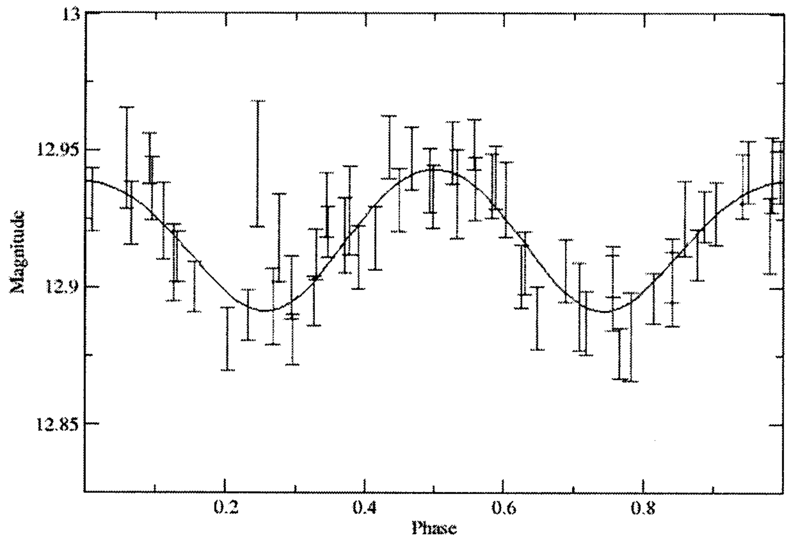

Figure 3. *B*-band Light Curve and ELC model

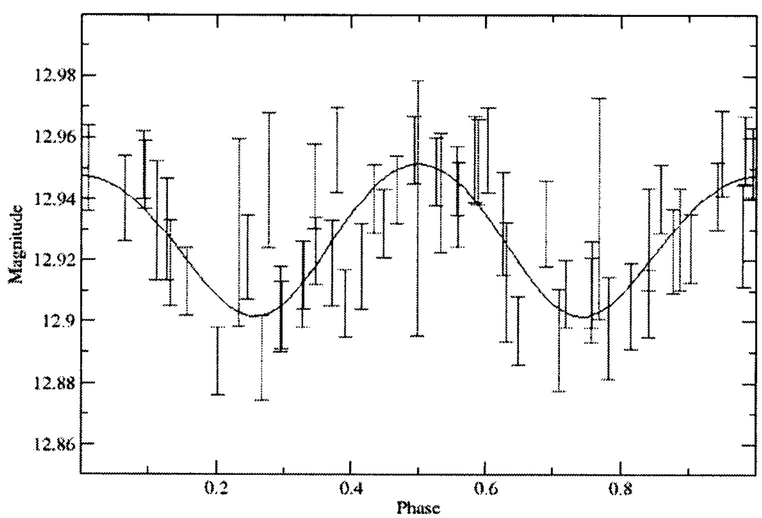

Figure 4. *V*-band Light Curve and ELC Model

Conclusions

The best fit model was created with the compact object's mass at a very precise 3.98 $M_\odot$ which puts it solidly above the 3 $M_\odot$ limit for stable neutron stars, which by definition for a compact object makes this in the category of black holes.

LMC X-1	Previous Studies	New Results
Period (days)	4.2288	3.90947 ± 0.00010
Inclination (deg)	≈63?	66.2 ± 3.0
Radial Velocity (km/s)	...	69.95 ± 0.95
V_{rot} (km/s)	...	140± 5
Black Hole Mass ($M_\odot$)	4.0 - 10.0?	3.98 ± 0.19
Secondary Mass ($M_\odot$)	...	14.71± 0.83

Table 2. Results

Acknowledgements

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