14TH Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun
ASP Conference Series, Vol. ASPCS 384, 2008
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The *Spitzer* 24μm Photometric Light Curve of the Eclipsing M-dwarf Binary GU Boötis

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Abstract. We present a carefully controlled set of Spitzer 24 μm MIPS time series observations of the low mass eclipsing binary star GU Boötis (GU Boo). Our data cover three secondary eclipses of the system: two consecutive events and an additional eclipse six weeks later. The study's main purpose is the long wavelength characterization of GU Boo's light curve, independent of limb darkening and less sensitive to surface features such as spots. Its analysis allows for independent verification of the results of optical studies of GU Boo. Our mid-infrared results show good agreement with previously obtained system parameters. In addition, the analysis of light curves of other objects in the field of view serves to characterize the photometric stability and repeatability of *Spitzer's* MIPS-24 at flux densities between approximately 300–2,000μJy. We find that the light curve root mean square about the median level falls into the 1–4% range for flux densities higher than 1 mJy.

1. Why is GU Boötis Important?

GU Boötis is a nearby, low-mass detached eclipsing binary system, consisting of two nearly equal mass M-dwarfs (López-Morales & Ribas 2005). It is one of currently very few known nearby (< 200 pc) double-lined, detached eclipsing binary (DEB) systems composed of two low-mass companions (López-Morales 2007). Eclipsing binaries can be used as tools to constrain fundamental stellar properties such as mass, linear radius, and effective temperature. Given the fact that over 70% of the stars in the Milky Way are low-mass objects with $M < 1M_{\odot}$ (Henry et al. 1997), coupled with the considerable uncertainty over the mass-radius relation for low-mass stars, objects such a GU Boötis are of particular interest in exploring the low-mass end of the Hertzsprung-Russell Diagram.

The characterization of the effects of limb darkening and star spots introduces free parameters and thus statistical uncertainty in the calculation of the stellar radii and masses. Using the *Spitzer Space Telescope*, we obtained 24 μm time series observations of three separate instances of GU Boo's secondary eclipse (see Table 1) to create a light curve far enough in the infrared to not be contaminated by the effects of limb darkening and star spots.

A further goal of our study is to characterize the photometric stability of the Multiband Imaging Photometer (MIPS) on *Spitzer* at 24 μm over short and long time scales. Time-series observing is atypical (albeit increasingly common) for *Spitzer* which is the reason why there are very few published photometric light curves based on *Spitzer* observations. The recent spectacular observations of primary and secondary eclipses of transiting planets are notable exception (see for instance Charbonneau et al. 2005; Deming et al. 2005). Of these, the Deming et al. (2005) study was performed at 24 μm. We therefore observed two consecutive secondary eclipses of GU Boo about 12 hours apart (observing sets 1 and 2), and then a third event about six weeks later (observing set 3). Table 1 gives an overview.

We describe our MIPS-24 observations and data reduction procedure in §2, present our results concerning GU Boo's light curve and the photometric stability of *Spitzer* and MIPS-24 in §3, and summarize in §4.

2. Observations and Data Reduction

We used MIPS-24 aboard the *Spitzer Space Telescope* (Werner et al. 2004) to observe GU Boötis in February and April of 2006, as outlined in Table 1. MIPS-24, the 24 μm array, is a Si:As detector with 128 $\times$ 128 pixels, an image scale of 2.55" pixel^{-1}, and a field of view of 5.4' $\times$ 5.4' (Rieke et al. 2004). Our exposures were obtained using the standard MIPS 24 μm small field photometry pattern (for details, see, for instance, Richardson et al. 2006).

Our goal was to observe three independent secondary eclipses of GU Boo: two consecutive ones and another one several weeks after the first two. Of our total of nine of *Spitzer's* Astronomical Observation Requests (AORs), three were used for each secondary eclipse event (see Table 1). Each AOR contained eight observing cycles with 36 individual exposures each. The first exposure in each cycle is 9s long, the subsequent 35 are 10s long. The first two exposures of every cycle were discarded due to a "first frames effect". This procedure left 34 frames per cycle, 272 frames per AOR, 816 frames per secondary eclipse event, and 2448 frames for the entire project (all 10s exposure time)[1].

The MIPS-24 data are provided by the *Spitzer Archive* in the (flatfielded) Basic Calibrated Data (BCD) format. We applied further post-processing to these data in order to correct for small scale artifacts, in particular using IRAF's[2]

[1]For background information on the *Spitzer* and MIPS operations, we refer the reader to the Spitzer Observer's Manual (SOM – http://ssc.spitzer.caltech.edu/documents/som/). For information specifically related to MIPS data reduction, please consult the MIPS Data Handbook (MDH – http://ssc.spitzer.caltech.edu/mips/dh/) and Gordon et al. (2005).

[2]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc, under cooperative agreement with the National Science Foundation.

Table 1. Spitzer MIPS-24 observations of GU Boötis

Date (2006)	MIPS Campaign	Obs. Set	AORs	Exposures[a]
Feb 20	*MIPS006500*	1	*16105472*	860
			16105216	
			16104960	
Feb 21	*MIPS006500*	2	*16104704*	860
			16104448	
			16104192	
Apr 01	*MIPS006700*	3	*16103936*	860
			16103680	
			16103424	

[a]10 seconds per exposure.

CCDRED package to remove the weak "jailbar" features in the images (as described in the MDH).

The *Spitzer* software package mopex (Makovoz & Khan 2005; Makovoz & Marleau 2005) was used for co-adding the individual MIPS frames into mosaics of 17 frames, using overlap correction and outlier rejection in the process. The choice of 17 frames was made (1) to obtain a high signal-to-noise ratio (SNR) for a measured stellar flux density in a resulting combined image and subsequent data point in the respective star's light curves, (2) to maintain a sufficiently high effective observing cadence to temporally resolve elements of GU Boo's light curve, and (3) not to be forced to combine frames from different cycles into a single light curve data point (see Table 1). The interpolated, remapped mosaics have a pixel scale of 2.45" pixel^{-1}. We show in Figure 1 the MIPS-24 field of view of GU Boötis.

For photometric reductions of the mosaiced images, we utilized the apex component of mopex to perform point-source extraction as described in Makovoz & Marleau (2005)[3]. This step included background subtraction of the images, and the fitting of a resampled point response function (PRF), derived from our own data. In order to match the PRF centroid as closely as possible to the centroid of the stellar profile, the first Airy ring was initially subtracted from the stellar profile, and detection was then performed on the resulting image.

3. Results

3.1. Analysis of GU Boo's Light Curve

We show in Fig. 2 the phased light curve of GU Boo. Based on preliminary light curve fitting to the relative flux density levels (scaled to magnitudes) shown in Figure 2, we find that our results are consistent with the system parameters

[3]Also see information on apex at http://ssc.spitzer.caltech.edu/postbcd/apex.html and the User's Guide at http://ssc.spitzer.caltech.edu/postbcd/doc/apex.pdf

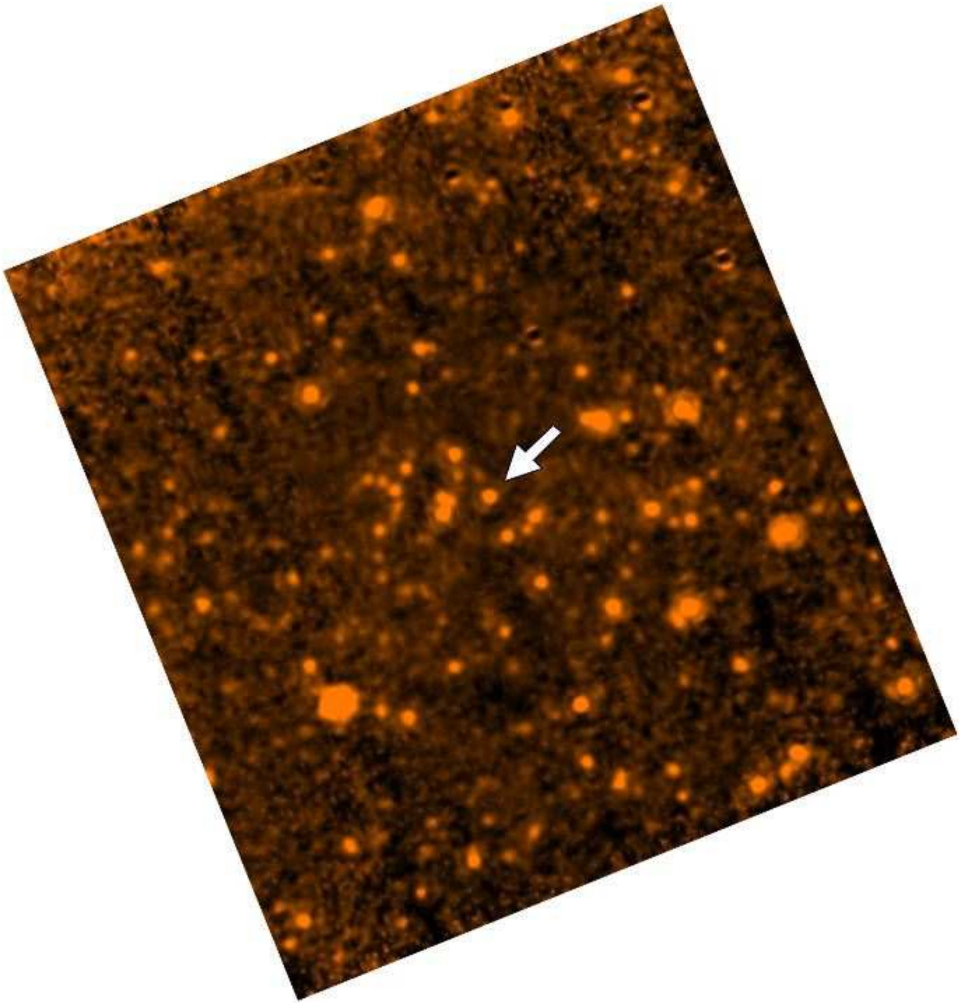

Figure 1. A *Spitzer* MIPS 24 μm mosaic of GU Boötis (marked with arrow at the center of the image). This mosaic was created using all 272 frames in one AOR and is about 5 arcmin on the side. North is up, east is to the left.

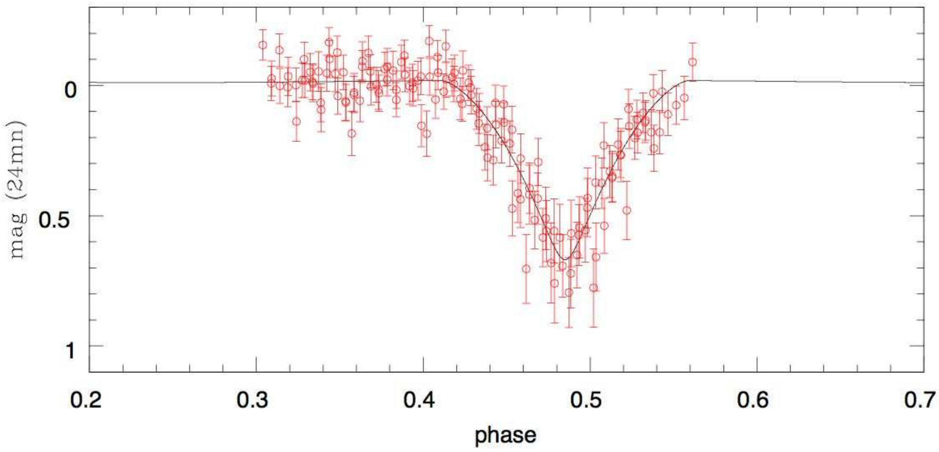

Figure 2. Folded 24 μm light curve for all 3 observed secondary eclipses of GU Boo. The preliminary fit is overlaid. The ordinate is scaled to 24 μm magnitudes with the zero point corresponding to the out-of-eclipse flux density level.

derived from the optical study of the system in López-Morales & Ribas (2005). The orbital period and initial epoch of the primary eclipse were set to the values given in the ephemerides equation derived by López-Morales & Ribas (2005). We further fixed the mass ratio and the radius ratio of the stars, as well as the eccentricity of the system (e=0) to the values obtained in that work. We assumed no limb darkening effects in the light curves, as expected for observations that far into the infrared (Claret et al. 1995; Richardson et al. 2006; Ciardi et al. 2007, and references therein), and no significant gravitational darkening or reflection effects, based on the spherical shape of the stars and the similarity in effective temperatures. All these are reasonable assumptions, based on the results of the study of GU Boo at visible wavelengths, and they are in fact hard to test in detail, given the photometric precision of the *Spitzer* light curve at this flux density level. Table 2 gives our estimates of GU Boo's system parameters.

Table 2. GU Boo System Parameters

Parameter	Value
Orbital Period (days)[a]	0.488728 ± 0.000002
Orbital Eccentricity[a]	0 (fixed)
Mass Ratio (M2/M1) [a]	0.9832 ± 0.0069
Radius of Secondary Component ($R_\odot$)	0.66 ± 0.02 (0.62)[a]
Orbital Inclination i (degrees)	89.3 ± 0.8 (87.6)[a]

[a]From López-Morales & Ribas (2005).

3.2. MIPS-24 Photometry Stability

Figure 3 shows the fractional rms around median values for all objects with more than 72 out of a total of 144 observational epochs for each individual observing set as well as for the three sets combined. Observing sets 1 and 2 were obtained during the MIPS006500 campaign, observing set 3 during MIPS006700 (Table 1). We find that inter-set repeatability of *Spitzer's* MIPS-24 is comparable to its repeatability within a set, both in terms of median flux density level as well as rms values. For the objects with a flux density in excess of 1 mJy, the rms values approach the 1–4 % level. The light curves of all objects in the field (other than GU Boo itself) are flat with different amounts of random scatter around the median flux density level.

4. Summary

We used MIPS-24 onboard the *Spitzer Space Telescope* to obtain time-series photometry of the M-dwarf DEB GU Boo. Our observations cover three secondary eclipse events, two consecutive ones and a further event six weeks later. Our mid-IR analysis of GU Boo's light curve is less affected by stellar surface features than its optical counterpart. The results show good agreement with the previously obtained system parameters based on optical and near-IR work. Finally, we find that the repeatability of MIPS-24 photometry is consistent over all temporal scales we sampled: within an observing set and on time scales of 24 hours and six weeks.

Acknowledgments. We gratefully acknowledge the availability of *Spitzer* Director's Discretionary Time (DDT) for this project. We furthermore thank D. Frayer, S. Carey, J. Colbert, and P. Lowrance for their help with the MIPS data reduction pipeline.

References

Charbonneau, D., et al. 2005, ApJ, 626, 523
Ciardi, D. R., et al. 2007, ApJ, 659, 1623
Claret, A., Diaz-Cordoves, J., & Gimenez, A. 1995, A&AS, 114, 247
Deming, D., Seager, S., Richardson, L. J., & Harrington, J. 2005, Nat, 434, 740
Gordon, K. D., et al. 2005, PASP, 117, 503
Henry, T. J., Ianna, P. A., Kirkpatrick, J. D., & Jahreiss, H. 1997, AJ, 114, 388
Makovoz, D., & Khan, I. 2005, Astronomical Data Analysis Software and Systems XIV, 347, 81
Makovoz, D., & Marleau, F. R. 2005, PASP, 117, 1113
López-Morales, M., & Ribas, I. 2005, ApJ, 631, 1120
López-Morales, M. 2007, ApJ, 660, 732
Richardson, L. J., Harrington, J., Seager, S., & Deming, D. 2006, ApJ, 649, 1043
Rieke, G. H., et al. 2004, ApJS, 154, 25
Werner, M. W., et al. 2004, ApJS, 154, 1

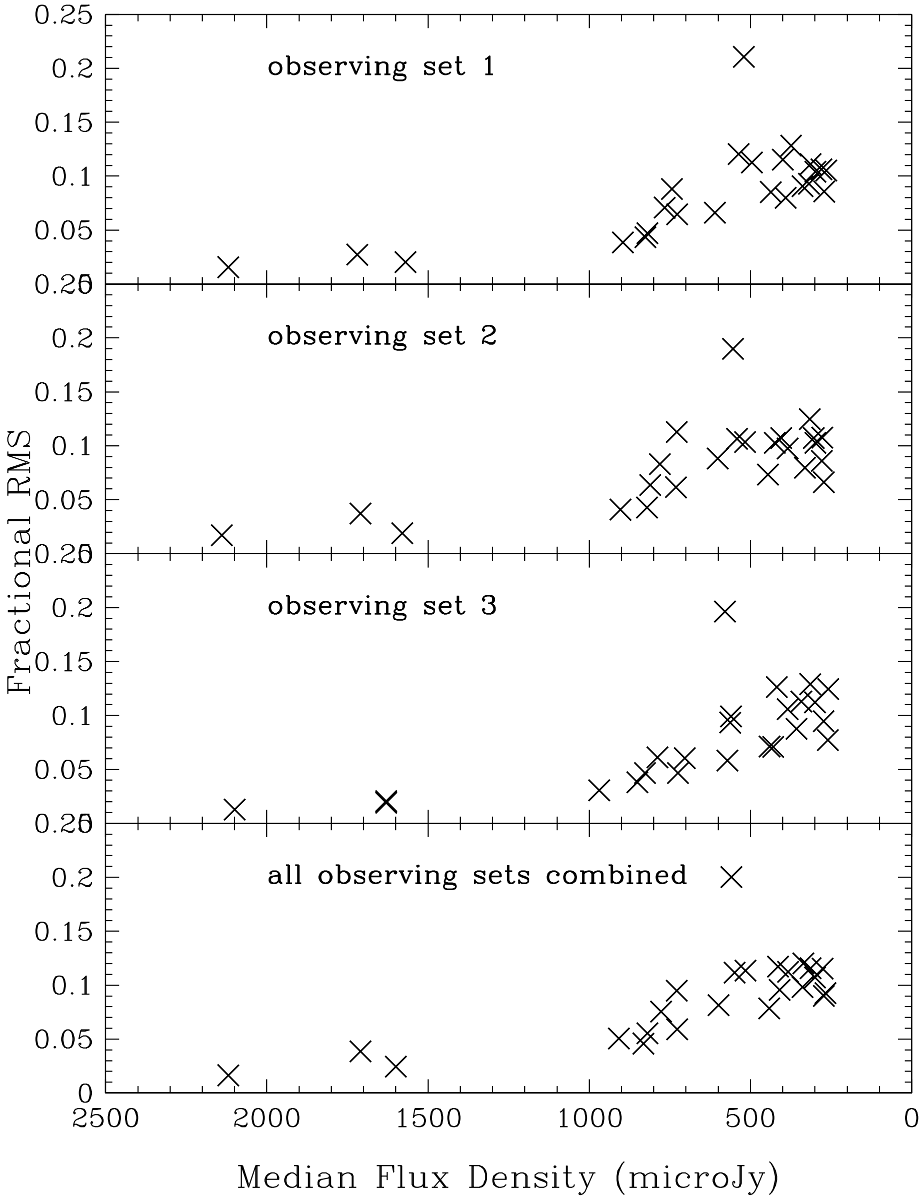

Figure 3. A plot of median flux density versus fractional rms for the 24 stars that have photometry for more than 72 out of 144 observational epochs. Shown are the individual 3 observing sets (see Table 1) to illustrate the repeatability of *Spitzer*/MIPS-24 within individual observing sets, as well as a plot of all 3 sets combined (to show the inter-set stability). The data point with the highest fractional rms is GU Boo.