Pushing the (Convective) Envelope: Imaging Spotted Stellar Surfaces with Optical Interferometry

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Abstract. Recent advances in interferometric capabilities allow for detecting submilliarcsecond structures on stellar surfaces. The combination of Georgia State University's Center for High-Angular Resolution Astronomy (CHARA) with the Michigan InfraRed Combiner (MIRC) allows for direct imaging with high-spatial resolution of stellar surfaces, including the ability to detect starspots. We aim to image starspots with the combination of CHARA/MIRC on the giant primary stars of RS CVn systems. In addition to detecting surface features, we compare the results of simultaneous interferometric, spectroscopic, and photometric observations of these systems. During the analysis of our data, our efforts have yielded detections of ellipsoidal variations of the primary giants as well as direct detections of the secondary stars. Here, we give an overview of interferometric stellar imaging efforts and our recent results of the spotted RS CVn star σ Geminorum.

1. Introduction

The advantage of imaging with interferometric data over other imaging techniques (e.g. spectroscopic and photometric) is that direct images can be obtained with no fundamental limits to the technique. The only limit to interferometry is the size of arrays. Optical interferometry has only recently had the array size and beam combiners necessary for direct imaging (e.g. Monnier et al. 2007).

Georgia State University's Center for High-Angular Resolution Astronomy (CHARA Array) is the only optical interferometer capable of distinguishing features on stellar surfaces with its sub-milliarcsecond resolution. CHARA consists of six 1−m telescopes located at Mount Wilson Observatory (CA, USA) in a non-redundant Y-shaped configuration with a longest baseline of 331 m (ten Brummelaar et al. 2005). In order obtain the best coverage of the target, all six CHARA telescopes must be combined, which is only possible with the Michigan InfraRed Combiner (MIRC Monnier et al. 2004, 2006).

2. Interferometric Imaging

Direct imaging of stellar surfaces is a young field, only recently possible with the MIRC instrument at the CHARA Array. The first results of interferometric imaging with MIRC confirmed the oblate shape of the rapidly-rotating main sequence star Altair (α Aql, A7V; Monnier et al. 2007). Following the imaging of Altair, several other rapidly rotating stars were studied to reveal more oblate surfaces (Zhao et al. 2011). These targets are of particular interest due to the effects of gravity darkening; as a rotating stellar surface deviates from a sphere, the effective temperature on different regions of the surface changes as the gravity changes (von Zeipel 1924).

Binary systems are also common MIRC imaging targets. CHARA/MIRC resolved detail in the systems β Lyrae and Algol (Zhao et al. 2008; Baron et al. 2012, respectively) to show the interactions of each system's components through the distortion of the stars' shapes from filling their Roche lobes. The binary system ϵ Aurigae has also been imaged to reveal a companion with a disk eclipsing the primary supergiant star (Kloppenborg et al. 2010).

Recently, spot structures have begun to be resolved on stellar surfaces with interferometry. Baron et al. (2014) provide images of two spotted supergiants, T Per and RS Per. The spots present are due to temperature variations and are evidence of large convective cells on the stellar surfaces. Resolving starspots on smaller stars pushes the limits of the present capabilities of interferometry.

2.1 RS CVn Imaging

RS Canum Venitacorum (RS CVn) stars are typically binary systems that have been observed to have photometric variability (Hall 1976). The spots observed on the surfaces of giant and sub-giant primary stars of RS CVn systems are not the result of large convective cells, but rather areas of decreased temperature due to strong magnetic fields suppressing convection (Strassmeier 2009). The spotted stellar surfaces of RS CVns are prime targets for indirect imaging with spectroscopic and photometric data (e.g. Korhonen et al. 2010; Roettenbacher et al. 2011).

Preliminary studies of the giant primary star of the RS CVn λ Andromedae (λ And) using interferometric imaging have shown promise for the current state of interferometry to be capable of imaging sub-milliarcsecond details on stellar surfaces (Parks et al. 2011, in prep.). Although these studies of the starspots of λ And show the advances of imaging with interferometry, comparisons to the well-established imaging techniques of Doppler and light-curve inversion imaging need to be made.

2.2 σ Geminorum

σ Geminorum (σ Gem, HD 62044) is an RS CVn system with a K-giant primary and main sequence companion previously only inferred by radial velocity shifts (Herbig & Spalding 1953). Recent studies of archival photometry have indicated the presence of two long-lived spots on nearly opposite sides of the primary (e.g. Henry et al. 1995; Kajatkari et al. 2014).

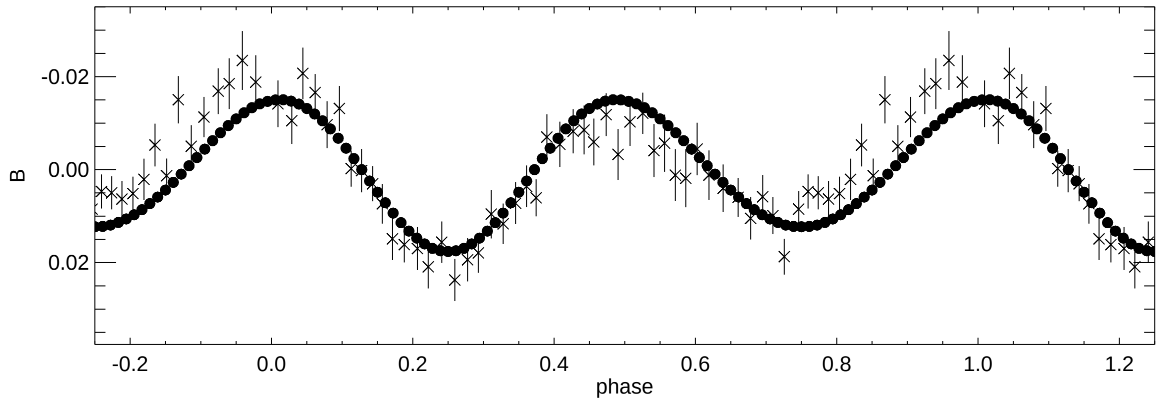
While analyzing our contemporaneous interferometric, spectroscopic, and photometric data sets of RS CVn systems, several previously undetected features of the systems have been revealed. In using a slightly expanded version of the data set used by Kajatkari et al. (2014), we folded and binned the light curve to reveal the presence of a sinusoid-like periodic photometric variation. The gravity of the companion star is strong enough to distort the shape of the primary star causing the primary to be ellipsoidal in shape. These ellipsoidal variations contribute to the signatures observed in the light curves and should be considered while analyzing the starspots (Roettenbacher et al. in prep., see Figure 1)).

In four nights of interferometric data, we were able to directly detect the companion star, constraining the orbital solution (see Figure 2). The secondary star is 250 times fainter than the primary star. The component masses are approximately 1.1 $M_\odot$ and 0.7 $M_\odot$ (Roettenbacher et al. in prep.).

3. Conclusions and Future Work

With the advancements in interferometry made possible by the sub-milliarcsecond resolution of the CHARA Array and the imaging capabilities of the MIRC instrument, the surface features of stars can now be resolved. The simple spot structures due to convective cell motion have begun to be imaged (Baron et al. 2014). The first attempts to image the surfaces of RS CVns have been made (Parks et al. 2011, in prep.) and new interferometric images will soon be compared to contemporaneous images reconstructed from spectroscopic and photometric data.

The serendipitous detections of ellipsoidal variations and companions of spotted RS CVn targets allow for a more complete understanding of the stellar systems. In turn, the images and models resulting from our contemporaneous data sets will be vital to advancing imaging



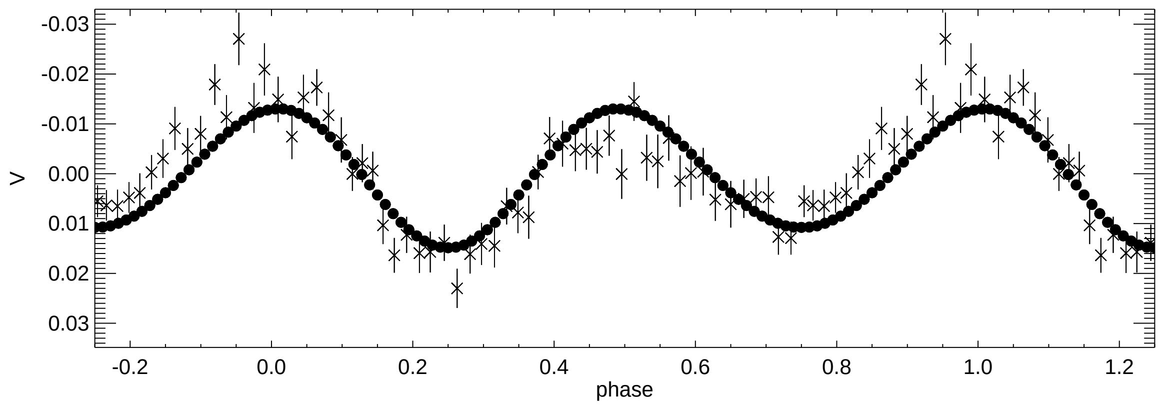


Figure .1: Binned B and V archival light curves of σ Gem folded over the orbital period plotted with a model light curve. The observed data are plotted with the 'x' symbol with error bars for the $1-\sigma$ standard deviation within each bin. The black circles are reconstructed light curves for the orbital parameters, allowing for ellipsoidal variations in the primary star (Roettenbacher et al. in prep.).

techniques and understanding stellar magnetic phenomena. We will apply our analysis to contemporaneous data sets of several RS CVn systems.

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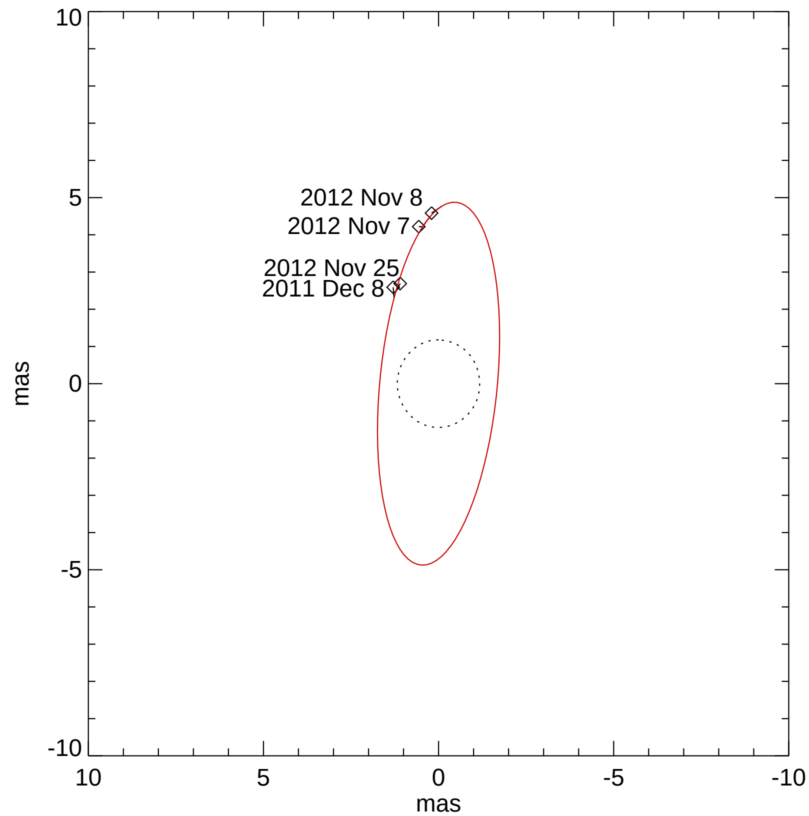

Figure .2: Visual orbit of σ Geminorum. The black diamonds indicate our four interferometric detections of the secondary star. The red ellipse is our orbit fit. The dotted ellipse is the outline of the primary star (Roettenbacher et al. in prep.).

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