The Nature of the Variable Galactic Center Source GCIRS 16SW
Revisited:
A Massive Eclipsing Binary

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ABSTRACT

We present a re-analysis of our $H$- and $K$-band photometry and light-curves for GCIRS 16SW, a regular periodic source near the Galactic center. These data include those presented by DePoy et al. (2004); we correct a sign error in their reduction, finding GCIRS 16SW to be an eclipsing binary with no color variations. We find the system to be an equal mass overcontact binary (both stars overfilling their Roche lobes) in a circular orbit with a period $P = 19.4513$ days, an inclination angle $i = 71°$. This confirms and strengthens the findings of Martins et al. (2006) that GCIRS 16SW is an eclipsing binary composed of two $\sim 50 M_\odot$ stars, further supporting evidence of recent star formation very close to the Galactic center. Finally, the calculated luminosity of each component is close to the Eddington luminosity, implying that the temperature of 24400 K given by Najarro et al. (1997) might be overestimated for these evolved stars.

Subject headings: Galaxy: center — stars: individual (GCIRS 16SW) — stars: binaries: eclipsing

1. Introduction

Standard star formation modes are thought to break down near a supermassive black hole (SMBH), raising the question of whether or not star formation near a SMBH is possible, and if so, through what mechanism (Navakshin & Sunyaev 2003). Our own Galaxy provides

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us with a unique opportunity to study individual stars in the presence of a SMBH, namely, Sgr A*. Direct observations of massive, and therefore young, stars close to Sgr A* indicate that there has been recent star formation at the Galactic center (Lebofsky et al. 1982).

GCIRS 16SW (hereafter IRS16SW) is a variable source near the Galactic center (\(\alpha = 17^{\mathrm{h}} 45^{\mathrm{m}} 40^{s} 1\), \(\delta = -29^\circ 00^\prime 29^\prime\prime\), J2000.0). Ott et al. (1999) reported that the source is regularly variable and suggested that it could be a binary star with very massive components. DePoy et al. (2004) confirmed the period of the object, but argued that the source was more likely a pulsating variable. Recently, however, Martins et al. (2006) reported spectroscopic observations of IRS16SW that showed radial velocity variations consistent with a binary composed of two massive stars.

Prompted by the convincing nature of the radial velocity variations seen by Martins et al. (2006) we have re-analyzed the data presented by DePoy et al. (2004) as well as additional data from the same observing campaign. We find that the original data reduction process was seriously flawed. In particular, the color variation, light-curve asymmetry, and sign of the brightness variations that DePoy et al. presented are artifacts of the data reduction process.

In this Letter, we report on the re-analysis of the DePoy et al. data. We find that there is no color change in IRS16SW over its variations and that the shape of the light curve is consistent with an eclipsing binary system. The new results are consistent with Martins et al. (2006) and confirm that IRS16SW is a binary composed of two massive stars. In \(\S2\) we describe the observations and present the data, in \(\S3\) we describe the best-fit model to the light-curve, and in \(\S4\) we discuss and summarize the results.

2. Observations

Observations of the Galactic center in the \(H\) (1.6\(\mu\)m) and \(K\) (2.2\(\mu\)m) bands were made at the Cerro-Tololo Inter-American Observatory (CTIO)/Yale 1-m telescope using the facility optical/infrared imager (ANDICAM; see DePoy et al. 2003 for details). ANDICAM has a pixel scale of 0\(\prime\)22 pix\(^{-1}\) on a 1024 \(\times\) 1024 array. Both \(H\)- and \(K\)-band images were taken in the 2001 and 2002 observing seasons; \(H\)-band data were also obtained in 2000. (The DePoy et al. 2004 analysis includes only the 2001 data.) The observing campaign consists of every usable night from UTC 2000 August 13 (HJD 2451769.5) through UTC 2000 October 14 (HJD 2451831.5), UTC 2001 May 20 (HJD 2452049.5) through UTC 2001 November 3 (HJD 2452216.5), and UTC 2002 June 9 (HJD 2452434.5) through UTC 2002 September 25 (HJD 2452542.5). Each night, a set of seven slightly offset images were obtained and then
combined and trimmed to form a final nightly image. The $H$-band images consist of 30 s exposures, and it took about four minutes to obtain the group of seven images; the $K$-band images consist of 10 s exposures and took about two minutes to obtain.

The final $512 \times 512$ pixel images, corresponding to a field of view of $112 \times 112$ arcseconds, are approximately centered on the Galactic center. After image quality cuts were made, there are a total of 144 $H$-band and 137 $K$-band images. The seeing ranges from $0''93$ to $1''93$ full-width half maximum; in general, the $H$-band images are of higher quality (typical seeing $\sim 1''3$) than the $K$-band (with typical seeing $\sim 1''45$).

Because the field is crowded, we reduced the data using the ISIS difference image analysis package (Alard 2000; Hartman et al. 2004). This analysis revealed a sign error in the original DePoy et al. (2004) reduction; IRS16SW is clearly an eclipsing binary. Because IRS16SW is subject to significant blending—there are roughly half a dozen sources in the Ott et al. (1999) catalog within about one arcsecond of IRS16SW—we calibrated our light-curves with the Ott et al. (1999) data as presented by Martins et al. (2006). The Martins et al. (2006) $K$-band photometry gives a mean magnitude of 0.2 mag higher than the Ott et al. (1999) mean, and includes two more seasons of data.

Ott et al. found a variability amplitude of 0.55 mag; using DAOPhot photometry to scale the ISIS fluxes, we find an amplitude of $\sim 0.35$ mag in both $H$ and $K$ (see Hartman et al. 2004, Appendix B). This substantial amplitude difference is indicative of significant blending in our data. We used the period of 19.45 days reported by DePoy et al. (2004) and Martins et al. (2006) to scale our $K$-band light-curve to have the same mean magnitude and amplitude as the Martins et al. data. There were 110 nights for which data were obtained in both the $H$- and $K$-bands, providing contemporaneous measurements of the $H - K$ color.

Using the DAOPhot photometry, we find a constant $H - K$ color with an rms of 0.05 mag; this color does not vary with time, phase, $H$-, or $K$-band magnitude, as shown in Figure 1. Lacking properly calibrated $H$-band data, we scaled the similarly blended $H$-band data to have the same amplitude and mean magnitude as the $K$-band data. These scaled light-curves form the basis of our analysis; Table 1 gives the final scaled time-series photometry.

3. Light Curve Analysis

We simultaneously fit the 144 $H$-band and 184 $K$-band points (including the Martins et al. $K$-band points, except for two noisy points at HJD 2498704 and 2499908) using the October 2005 version of the Wilson-Devinney (WD) code (Wilson & Devinney 1971; Wilson 1979, 1990) in the overcontact mode (MODE 3). We fixed $T_{\text{eff}1} = 24400$ K as estimated by
Najarro et al. (1997) and used the square-root limb darkening law, taking the values of the limb darkening coefficients from Claret (2000) for a LTE ATLAS9 (Kurucz 1993) stellar atmosphere model with $T_{\text{eff}} = 24000$ K, $\log(g) = 3.0$ (cgs), turbulent velocity of 2 km s$^{-1}$ and solar metallicity. We fixed gravity brightening exponents and albedos to unity from theoretical values for stars at such temperatures. We assumed equal masses, circular orbits, and synchronous rotation, fitting for 7 parameters: the period $P$, time of primary eclipse $T_{\text{prim}}$(HJD), inclination $i$, $T_{\text{eff}}$, the luminosity of the primary in each band ($L_{1H}, L_{1K}$) and the surface potential ($\Omega_1 = \Omega_2$, see Wilson 1979, eq. 1). We defined convergence to be when the corrections for all adjusted parameters were smaller than their respective standard or statistical errors after three consecutive iterations. The best fit parameters are shown in Table 2. The ephemeris is

$$T_{\text{prim}} = 2451775.102 \pm 0.032 + 19.4513 \pm 0.0011 \times E \text{(HJD)}. \quad (1)$$

A good fit required that the stars overfill their limiting Roche lobes, which justifies using the overcontact mode of WD. Martins et al. (2006) adopted the largest filling factor allowed by NIGHTFALL (1.3); we calculate a larger fill-out factor (as defined by Mochnacki & Doughty 1972) of $F = 1.44$. The critical surface potentials for the inner and outer surfaces under the above assumptions are $\Omega_{\text{in}} = 3.75$ and $\Omega_{\text{out}} = 3.21$. Assuming different values for the mass ratio $q$ also produced good fits. However, a photometric mass ratio is not well constrained by our photometry; therefore, we did not attempt to solve for it. The inclination we derive is $i = 71^\circ$, in agreement with Martins et al. (2006); however, if there is still unaccounted for blending, then the inclination angle could be larger.

In Figures 2 and 3 we show the $H$- and $K$-band light curve model fit for IRS16SW. The Martins et al. (2006) data are plotted with unfilled symbols in Figure 3. Error bars for our data are set to 0.04 mag, corresponding to the typical variation seen for a constant star of similar magnitude (Peeples et al., in preparation). The fact that the data are fit well under the assumption of circular orbits is an indication that this assumption is sound; these data give no evidence for an eccentric orbit. The eccentricity of $e = 0.09$ found by Martins et al. (2006) is derived from their radial velocity curve, which tends to yield nonzero eccentricities (Lucy & Sweeney 1971). Furthermore, the circularization time for a system with these physical characteristics (discussed below) is only tens of thousands of years (Zahn 1975, 1977), making it unlikely that we are observing IRS16SW pre-circularization.

From the definition of $\Omega$, WD calculates the following best fit fractional radii for both stars in units of the orbital separation: the polar radius, $r_{\text{pole}} = 0.39$; the radius in the plane of revolution and perpendicular to the line connecting the stars’ centers, $r_{\text{side}} = 0.41$, and the radius in the direction of L2, $r_{\text{back}} = 0.47$. The orbital separation of Martins et al. (2006), $(a_1 + a_2) \sin i = 132.8 \pm 4.4 R_\odot$, yields physical radii of $R_{\text{pole}} = 54.5 \pm 1.8 R_\odot$, ...
$R_{\text{side}} = 58.2 \pm 1.9 \, R_\odot$, and $R_{\text{back}} = 62.7 \pm 2.1 \, R_\odot$. The WD visualization for this system is shown in Figure 4.

4. Discussion and Conclusion

Using Kepler’s law, Martins et al. (2006) find $M_1 \approx M_2 \approx 50 M_\odot$, placing the components of IRS16SW among the most massive stars known. Until recently, the most massive stars measured in binaries were R136-38 in the Large Magellanic Cloud (57 $M_\odot$, Massey et al. 2002) and WR 22 (55 $M_\odot$, Rauw et al. 1996, Schweickhardt et al. 1999), an evolved star in our Galaxy. The current heavyweight champion is a Wolf-Rayet binary, WR 20a (82 & 83 $M_\odot$, Rauw et al. 2004, Bonanos et al. 2004), in the young Galactic cluster Westerlund 2.

The luminosity of IRS16SW poses a problem. Using a radius of $R = 59.7 R_\odot$ (the mean radius given by WD for an orbital separation of 140.6 $R_\odot$) and an effective temperature of $T_{\text{eff}} = 24400$ K (Najarro et al. 1997), we can estimate the luminosity $L = 4\pi R^2 \sigma T_{\text{eff}}^4$ of each component as $4.4 \times 10^{39}$ erg s$^{-1}$. The non-sphericity of IRS16SW will only drive this luminosity higher. For comparison, the Eddington luminosity of a $50 M_\odot$ star is $L_{\text{edd}} = 1.3 \times 10^{38} (M/M_\odot) = 6.5 \times 10^{39}$ erg s$^{-1}$. It is highly unlikely that each component of IRS16SW has been radiating stably at nearly their Eddington luminosities for eleven years (Humphreys & Davidson 1994); the combined photometry of Ott et al. (1999) and this work span 1992–2002. Assuming the orbital separation as calculated by Martins et al. (2006) is correct (if it is smaller, then $L/L_{\text{edd}}$ will be even larger), this calculation implies that the temperature of Najarro et al. (1997) is an over-estimate. A change in the assumed $T_{\text{eff}}$ affects the WD model parameters; specifically, a decrease in $T_{\text{eff}}$ by a few thousand degrees Kelvin will decrease the inclination angle $i$, and thus increase the masses of the stars, by more than the formal 1σ uncertainties given by WD.

A radial velocity curve for the secondary is necessary to determine the value of the mass ratio $q$. It remains a puzzle as to why IRS16SW does not appear to be a double-line spectroscopic binary. It is readily apparent from the depths of the eclipses that the two stars have near-equal fluxes and from the depth ratio that they have near-equal surface brightnesses, yet Martins et al. (2006) see only one set of spectroscopic lines. However, since the spectral features used by Martins et al. (2006) are wind lines, with strong characteristic P Cygni profiles (Najarro et al. 1997), differences in wind strength or small differences in the effective temperatures of the stars could easily conspire to make detection of the second set of lines difficult.

We confirm that GCIRS 16SW is a massive eclipsing binary with both stars overflowing
their Roche lobes. We find a refined orbital period of $19.4513 \pm 0.0011$ days and an inclination of $71^\circ$ with an assumed mass ratio of 1, supporting the findings by Martins et al. (2006) that the masses of the two stars are both $\sim 50 M_\odot$. The projected distance between IRS16SW and Sgr A* is 0.05 pc $\sim 11000$ AU (assuming a distance to the Galactic center of 7.6 kpc, Eisenhauer et al. 2005); in fact, IRS16SW is part of a moving group that is likely bound to Sgr A* (Lu et al. 2005; Paumard et al. 2006). As the lifetime of 50$M_\odot$ stars is $\sim 4$ Myr (Schaller et al. 1992), these observations are strong evidence that IRS16SW was formed within 0.1 pc of Sgr A* despite the tidal shear from the black hole which creates problems in star formation models.

We thank F. Martins for providing us with the Ott et al. (1999) K-band light-curve, Slavek Rucinski, Andy Gould, and John Beacom for useful discussions, and the anonymous referee for helpful suggestions. A. Z. B. acknowledges research and travel support from the Carnegie Institution of Washington through a Vera Rubin Fellowship. KS gratefully acknowledges support from NSF grant AST-0206331.

REFERENCES


Table 1. *H*- and *K*-band Photometry of GCIRS 16SW

<table>
<thead>
<tr>
<th>Band</th>
<th>HJD Scaled −2450000.</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1769.6620</td>
<td>9.630</td>
</tr>
<tr>
<td>H</td>
<td>1772.5868</td>
<td>9.730</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>2542.5417</td>
<td>10.041</td>
</tr>
<tr>
<td>K</td>
<td>2048.9194</td>
<td>9.886</td>
</tr>
<tr>
<td>K</td>
<td>2051.7765</td>
<td>9.527</td>
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<td></td>
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</tbody>
</table>

Note. — Both *H*- and *K*-bands are scaled to have the same amplitude and mean magnitude as the Ott et al. (1999) *K*-band data presented by Martins et al. (2006). All errors are set to 0.04 mag, corresponding to the typical variation seen for a constant star of similar magnitude (Peeples et al., in preparation). Table is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
Table 2. **Best-Fit Parameters From Combined H&K Light-Curve Analysis With Wilson-Devinney Program**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period, $P$</td>
<td>$19.4513 \pm 0.0011$ days</td>
</tr>
<tr>
<td>Time of primary eclipse, $T_{\text{prim}}$</td>
<td>$2451775.102 \pm 0.032$</td>
</tr>
<tr>
<td>Inclination, $i$</td>
<td>$70.85^{\circ} \pm 0.6^{\circ}$</td>
</tr>
<tr>
<td>Temperature ratio, $T_2/T_1$</td>
<td>0.96</td>
</tr>
<tr>
<td>Surface potential, $\Omega$</td>
<td>3.51</td>
</tr>
<tr>
<td>Light ratio in $H$, $L_2/L_1$</td>
<td>0.936</td>
</tr>
<tr>
<td>Light ratio in $K$, $L_2/L_1$</td>
<td>0.939</td>
</tr>
<tr>
<td>Radius, $r_{\text{pole},1} = r_{\text{pole},2}$</td>
<td>0.39</td>
</tr>
<tr>
<td>.......... $r_{\text{side},1} = r_{\text{side},2}$</td>
<td>0.41</td>
</tr>
<tr>
<td>.......... $r_{\text{back},1} = r_{\text{back},2}$</td>
<td>0.47</td>
</tr>
<tr>
<td>Secondary temperature, $T_2$</td>
<td>23500 K</td>
</tr>
<tr>
<td>Radius, $R_{\text{pole}}$</td>
<td>$54.5 \pm 1.8 , R_\odot$</td>
</tr>
<tr>
<td>.......... $R_{\text{side}}$</td>
<td>$58.2 \pm 1.9 , R_\odot$</td>
</tr>
<tr>
<td>.......... $R_{\text{back}}$</td>
<td>$62.7 \pm 2.1 , R_\odot$</td>
</tr>
</tbody>
</table>

Note. — First ten parameters are best-fit parameters from a combined $H&K$ light-curve analysis with the Wilson-Devinney (WD) program. The 1σ uncertainties given by WD are unrealistically small, and thus not listed. The radii $r_{\text{pole}}$, $r_{\text{side}}$, and $r_{\text{back}}$ are in units of the orbital separation. The final four (physical) parameters are based on the orbital separation, $(a_1 + a_2) \sin i = 140.6 \pm 4.7R_\odot$ and the assumed effective temperature of 24400 K for $T_1$ (Najarro et al. 1997).
Fig. 1.— $H - K$ color residuals for DAOPhot photometry versus calibrated $K$-band magnitude. No clear trend between color and magnitude is observed. The rms variation about a constant color is 0.05 magnitudes. The errorbar on the left shows the typical uncertainty in $H - K$ color for a constant star of similar magnitude. See §2 for further discussion.
Fig. 2.— Wilson-Devinney fit and residuals of an overcontact binary to the $H$-band light-curve of IRS16SW. The period is 19.4513 days; the model parameters have zero eccentricity and an inclination of 71°. The rms variation about the model fit is 0.06 magnitudes.
Fig. 3.— Wilson-Devinney fit and residuals of an overcontact binary to the $K$-band light-curve of IRS16SW. The filled circles are the data presented here; the open squares are the Martins et al. (2006) data. The period is 19.4513 days; the model parameters have zero eccentricity and an inclination of 71°. The rms variation about the model fit is 0.06 magnitudes.
Fig. 4.— Wilson-Devinney visualization of IRS16SW at an orbital phase of 0.12. Axes are in units of $R_\odot$. 