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THE NATURE OF THE VARIABLE GALACTIC CENTER SOURCE GCIRS 16SW REVISITED: A MASSIVE ECLIPSING BINARY

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ABSTRACT

We present a reanalysis 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.; 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 and an inclination angle $i = 71°$. This confirms and strengthens the findings of Martins et al. 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 24,400 K given by Najarro et al. might be overestimated for these evolved stars.

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

On-line material: machine-readable table

1. INTRODUCTION

Standard star formation modes are thought to break down near a supermassive black hole (SMBH), raising the questions of whether or not star formation near a SMBH is possible and, if so, through what mechanism (Nayakshin & Sunyaev 2005). Our own Galaxy provides 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 IRS 16SW) is a variable source near the Galactic center ($\alpha = 17^{h}45^{m}40.1^{s}$, $\delta = -29°00'29''$, 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 IRS 16SW 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 reanalyzed 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 reanalysis of the DePoy et al. data. We find that there is no color change in IRS 16SW 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 IRS 16SW is a binary composed of two massive stars. In § 2 we describe the observations and present the data, in § 3 we describe the best-fit model to the light curve, and in § 4 we discuss and summarize the results.

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2. OBSERVATIONS

Observations of the Galactic center in the *H* (1.6 μm) and *K* (2.2 μm) 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 0.22″ pixel^{-1} on a 1024 × 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 2,451,769.5) through UTC 2000 October 14 (HJD 2,451,831.5), UTC 2001 May 20 (HJD 2,452,049.5) through UTC 2001 November 3 (HJD 2,452,216.5), and UTC 2002 June 9 (HJD 2,452,434.5) through UTC 2002 September 25 (HJD 2,452,542.5). 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 5 minutes to obtain the group of seven images; the *K*-band images consist of 10 s exposures and took about 2 minutes to obtain.

The final 512 × 512 pixel images, corresponding to a field of view of 112″ × 112″, are approximately centered on the Galactic center. A total of 144 *H*-band and 137 *K*-band images passed the image quality cuts. The seeing ranges from 0.93″ to 1.93″ full width at half-maximum (FWHM); in general, the *H*-band images are of higher quality (typical seeing ∼1.3″) than the *K*-band images (with typical seeing ∼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; IRS 16SW is clearly an eclipsing binary. Because IRS 16SW is subject to significant blending—there are roughly half a dozen sources in the Ott et al. (1999) catalog within about 1″ of IRS 16SW—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

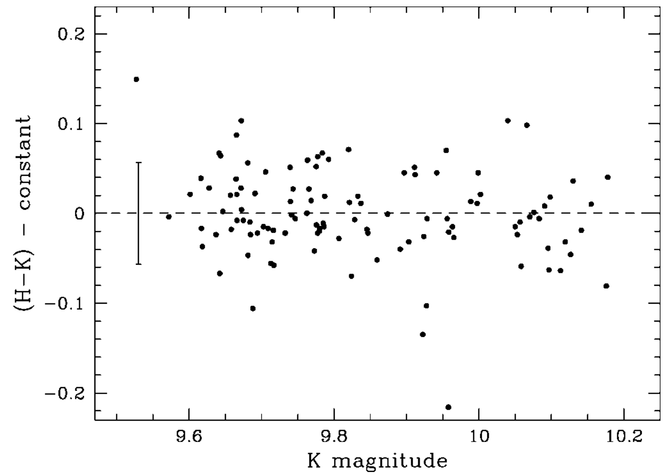

FIG. 1.—$H - K$ color residuals for DAOPhot photometry vs. calibrated *K*-band magnitude. No clear trend between color and magnitude is observed. The rms variation about a constant color is 0.05 mag. The error bar on the left shows the typical uncertainty in $H - K$ color for a constant star of similar magnitude. See § 2 for further discussion.

gives a mean magnitude of 0.2, 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 ∼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 2,498,704 and 2,499,908) using the 2005 October version of the Wilson-Devinney code (Wilson & Devinney 1971, hereafter WD; Wilson 1979, 1990) in the overcontact mode (mode 3). We fixed $T_{\mathrm{eff1}} = 24{,}400$ 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 $T_{\mathrm{eff}} = 24{,}000$ K, $\log g = 3.0$ (cgs), a 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 seven parameters: the period *P*, the time of primary eclipse T_{prim}(HJD), inclination *i*, T_{eff2}, 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

$$T_{\mathrm{prim}} = 2{,}451{,}775.102 \pm 0.032 + 19.4513 \pm 0.0011E \text{ (HJD)}. \quad (1)$$

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 (ver. 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 $\Omega_{\mathrm{in}} = 3.75$ and $\Omega_{\mathrm{out}} = 3.21$. 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 $i = 71°$, 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 IRS 16SW. The Martins et al. (2006) data are plotted with open squares in Figure 3. Error bars for our data

TABLE 1
H- AND *K*-BAND PHOTOMETRY OF GCIRS 16SW

Band	HJD − 2,450,000	Scaled Magnitude
H	1769.6620	9.630
	1772.5868	9.730
K	2048.9194	9.886
	2051.7765	9.527

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 (M. Peeples et al. 2007, in preparation). Table 1 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* AND *K* LIGHT-CURVE ANALYSIS WITH WD PROGRAM

Parameter	Value
Period, *P*	19.4513 ± 0.0011 days
Time of primary eclipse, T_{prim}	2,451,775.102 ± 0.032
Inclination, *i*	70.85° ± 0.6°
Temperature ratio, T_2/T_1	0.96
Surface potential, Ω	3.51
Light ratio in *H*, L_2/L_1	0.936
Light ratio in *K*, L_2/L_1	0.939
$r_{\mathrm{pole,1}} = r_{\mathrm{pole,2}}$	0.39
$r_{\mathrm{side,1}} = r_{\mathrm{side,2}}$	0.41
$r_{\mathrm{back,1}} = r_{\mathrm{back,2}}$	0.47
Secondary temperature, T_2	23500 K
R_{pole}	54.5 ± 1.8 $R_\odot$
R_{side}	58.2 ± 1.9 $R_\odot$
R_{back}	62.7 ± 2.1 $R_\odot$

NOTE.—The first 10 parameters are best-fit parameters from a combined *H* and *K* light-curve analysis with the WD program. The 1 σ uncertainties given by WD are unrealistically small and thus are not listed. The radii r_{pole}, r_{side}, and r_{back} are in units of the orbital separation. The final four (physical) parameters are based on the orbital separation, $(a_1 + a_2)\sin i = 140.6 \pm 4.7\ R_\odot$, and the assumed effective temperature of 24400 K for T_1 (Najarro et al. 1997).

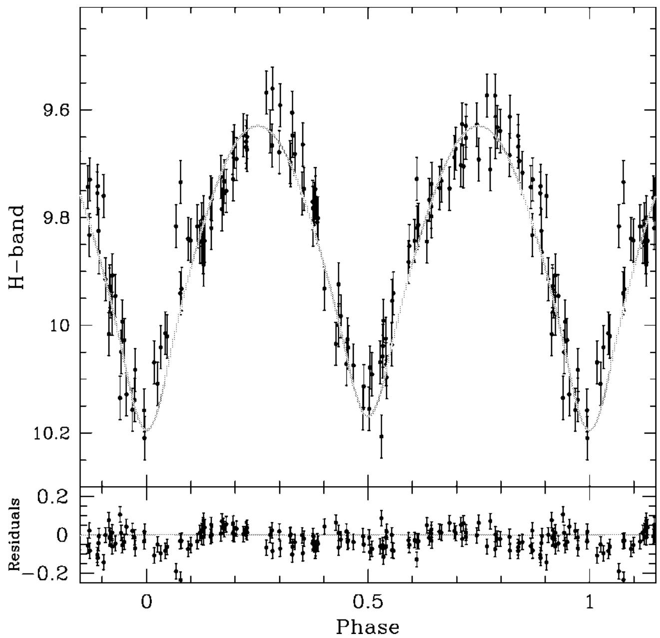

FIG. 2.—Wilson-Devinney fit and residuals of an overcontact binary to the *H*-band light curve of IRS 16SW. The period is 19.4513 days; the model parameters have zero eccentricity and an inclination of 71°. The rms variation about the model fit is 0.06 mag.

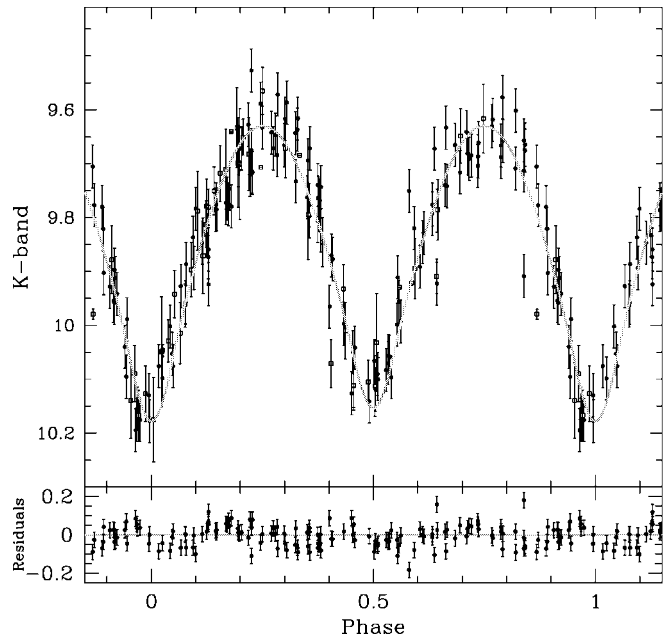

FIG. 3.—Wilson-Devinney fit and residuals of an overcontact binary to the *K*-band light curve of IRS 16SW. The filled circles are the data presented here; the open squares are the Martins et al. (2006) data. The period is 19.4513 days; the model parameters have zero eccentricity and an inclination of 71°. The rms variation about the model fit is 0.06 mag.

are set to 0.04 mag, corresponding to the typical variation seen for a constant star of similar magnitude (M. Peeples et al. 2007, 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 of 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 IRS 16SW precircularization.

From the definition of Ω, WD calculates the following best-fit fractional radii for both stars in units of the orbital separation: the polar radius, $r_{\rm pole} = 0.39$; the radius in the plane of revolution and perpendicular to the line connecting the stars' centers, $r_{\rm side} = 0.41$, and the radius in the direction of L2, $r_{\rm back} = 0.47$. 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 $R_{\rm pole} = 54.5 \pm 1.8\ R_\odot$, $R_{\rm side} = 58.2 \pm 1.9\ R_\odot$, and $R_{\rm back} = 62.7 \pm 2.1\ R_\odot$. 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 IRS 16SW 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 and 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 $T_{\rm eff} = 24400$ K (Najarro et al. 1997), we can estimate the luminosity $L = 4\pi R^2 \sigma T_{\rm eff}^4$ of each component as 4.4×10^{39} ergs s^{-1}. The nonsphericity of IRS 16SW will only drive this luminosity higher. For comparison, the Eddington luminosity of a 50 $M_\odot$ star is $L_{\rm Edd} = 1.3 \times 10^{38}(M/M_\odot) = 6.5 \times 10^{39}$ ergs s^{-1}. It is highly unlikely that each component of IRS 16SW has been radiating stably at nearly their Eddington luminosities for 11 years (Humphreys & Davidson 1994); the combined photometry of Ott et al. (1999) and this work spans 1992–2002. Assuming the orbital separation as calculated by Martins et al. (2006) is correct (if it is smaller, then $L/L_{\rm Edd}$ will be even

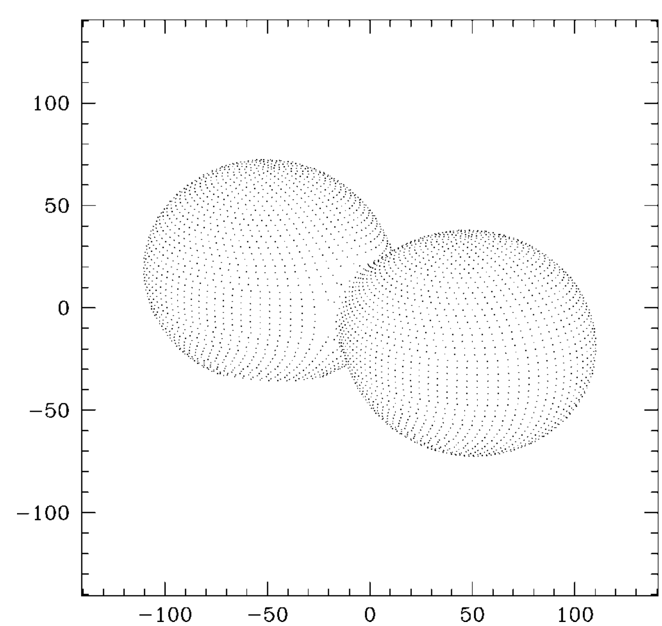

FIG. 4.—Wilson-Devinney visualization of IRS 16SW at an orbital phase of 0.12. Axes are in units of the solar radius.

larger), this calculation implies that the temperature of Najarro et al. (1997) is an overestimate. A change in the assumed $T_{\rm eff}$ affects the WD model parameters; specifically, a decrease in $T_{\rm eff}$ by a few thousand kelvins will decrease the inclination angle i, and thus increase the masses of the stars, by more than the formal 1 σ 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 IRS 16SW 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 ± 0.0011 days and an inclination of 71° 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 IRS 16SW and Sgr A* is 0.05 pc ∼ 11,000 AU (assuming a distance to the Galactic center of 7.6 kpc; Eisenhauer et al. 2005); in fact, IRS 16SW 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 ∼4 Myr (Schaller et al. 1992), these observations are strong evidence that IRS 16SW was formed within 0.1 pc of Sgr A*, despite the tidal shear from the black hole that creates problems in star formation models.

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