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GCIRS16SW: A MASSIVE ECLIPSING BINARY IN THE GALACTIC CENTER *

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ABSTRACT

We report on the spectroscopic monitoring of GCIRS16SW, an Ofpe/WN9 star and LBV candidate in the central parsec of the Galaxy. SINFONI observations show strong daily spectroscopic changes in the K band. Radial velocities are derived from the He I 2.112μm line complex and vary regularly with a period of 19.45 days, indicating that the star is most likely an eclipsing binary. Under various assumptions, we are able to derive a mass of $\sim$ 50 $M_{\odot}$ for each component.

Subject headings: Stars: binaries:eclipsing — Stars: early-type — Galaxy: center

1. INTRODUCTION

The central cluster constitutes one of the largest concentrations of massive stars in the Galaxy (Genzel et al. 2003). Nearly 100 OB and Wolf-Rayet stars are confined in a compact region of radius $\sim$ 0.5 parsec centered on the super-massive black hole associated with the radio source SgrA* (Paumard et al. 2006). Among this population of young massive stars, six are thought to be Luminous Blue Variables (LBV): IRS16NE, IRS16C, IRS16NW, IRS16SW, IRS33E and IRS34W (Paumard et al. 2004; Trippe et al. 2006). LBVs are evolved massive stars experiencing strong variability in both photometry and spectroscopy due to their proximity to the Humphreys-Davidson limit (Humphreys & Davidson 1994), a region of the HR diagram where the luminosity of the stars reaches the Eddington luminosity so that instabilities develop in their atmospheres, leading to strong mass ejection and drastic changes in the stellar properties ($T_{\rm eff}$, radius). The six stars mentioned above are only LBV "candidates" (LBVc) since they have not been observed to experience the strong outbursts and photometric changes typical of bona fide LBVs such as η Car (Davidson & Humphreys 1997). However, their luminosities and spectra are very similar to stars known to be "quiescent" LBV, i.e. stars having experienced an LBV event in the past and being now in a more stable phase. In addition, one of them - IRS34W - has shown photometric variability on timescales of months to years which was interpreted as the formation of dust from material previously ejected by an LBV outburst (Trippe et al. 2006).

Among these six stars, IRS16SW deserves special attention. This star was claimed to be a massive eclipsing binary by Ott et al. (1999) since its K band magnitude displays regular variations with a periodicity of 9.72 days. However, the absence of a second eclipse in the light-curve lead DePoy et al. (2004) to the conclusion that the binary scenario was not correct, and that IRS16SW was instead a pulsating massive star, a class of star predicted by theory but not observed so far.

Here, we present results of the spectroscopic monitoring of IRS16SW revealing periodic variations of radial velocities which are interpreted as the signature of a massive spectroscopic and eclipsing binary .

2. OBSERVATIONS AND DATA REDUCTION

We used SINFONI (Eisenhauer et al. 2003) on the ESO/VLT to obtain spectra of IRS16SW. Observations were carried out under seeing limited conditions and were performed on August 28$^{\rm th}$ - September 1$^{\rm st}$, September 4$^{\rm th}$, October 2$^{\rm nd}$, and October 4$^{\rm th}$ - 12$^{\rm th}$ 2005, and March 18$^{\rm th}$ - 21$^{\rm st}$ 2006. In order to get the best spectral resolution available with SINFONI (R = 4000) we restricted ourselves to the K band. Short exposures (2$\times$60 seconds) were sufficient to obtain S/N $\sim$ 30. Data reduction was performed as in Eisenhauer et al. (2005). The final spectra were subsequently carefully extracted from the "data cubes" by selecting a circular aperture (radius of 3 pixels) centered on the star and by subtracting from it an annulus of inner (outer) radius 3 (4) pixels. This procedure allowed a good removal of nebular contamination.

3. RESULTS

3.1. *Spectroscopic variability and radial velocities*

Fig. 1 shows the variation of the He I 2.112 μm and Brγ lines with time. It is obvious that not only the line shape but also the position of the centroid varies. In order to test the binary scenario, we have derived radial velocities (RV). For that purpose, we have used the line at 2.112 μm since it is less affected by wind emission than other lines and is formed closer to the photosphere, allowing a better estimate of the star's motion. This line is however a blend of at least two He lines, and synthetic spectra computed with atmosphere models reveal that the position of the strongest absorption part of the profile can vary by several 100 km s^{-1} around 2.112 μm depending on the stellar and wind properties. We have thus adopted this wavelength as our reference, but we stress that the absolute value of the RV may be systematically shifted compared to the real value due to this choice. In practice, we have measured the position of the maximum absorption trough in the line complex and computed the radial velocity from the wavelength shift

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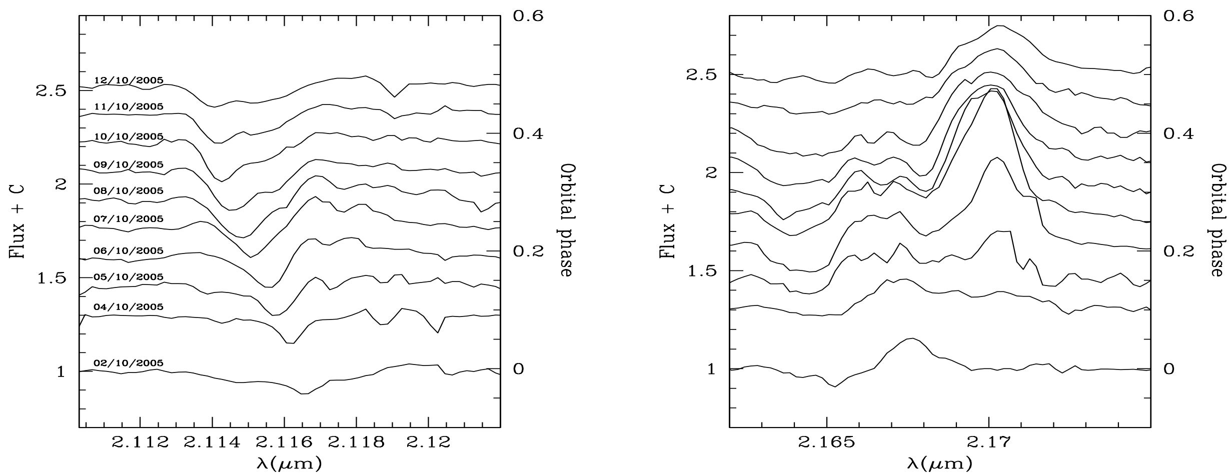

FIG. 1.— Montage of spectra of IRS16SW around the region of He I 2.112 μm (left) and Brγ (right) taken between October 2^{nd} and October 12^{th} 2005. The changes in both the line shape and position are clearly seen.

compared to the adopted reference wavelength. When the line shows a double peak, we have always measured the position of the deepest absorption part of the profile (which also turned out to always be the bluest). This implicitely assumes that if the star is a binary, this absorption is always produced by the same star. Note that when present, the two absorption peaks are separated by the theoretical spacing between the two Helium lines around 2.112 μm: 170 km s^{-1}. Hence we conclude that the second peak most likely comes from the same star. The derived RV are presented in Fig. 2 and follow very nicely an almost exact cosine curve (see below). This is a strong indication that IRS16SW is a binary star (and justifies a posteriori our method to derive RVs).

A period folding analysis applied to the RV curve gives 19.3 ± 0.4 days, in good agreement with the K band light-curve analysis. DePoy et al. (2004) derived a period of 9.725 ±0.005 days but argue that if this light-curve was to be produced by a binary star, the absence of second minimum should point to a system composed of two stars with the same K band luminosity, and consequently to a true period of 2 × 9.725 = 19.45 days. A re-analysis of the photometric data of Ott et al. (1999) in view of these new results confirms that a period of 19.447 ±0.011 days is indeed present in the period folding diagram (for a description of the method, see Ott et al. 1999). We conclude that IRS16SW is most likely a single line spectroscopic (SB1) and eclipsing binary with an orbital period of 19.45 days.

3.2. *Orbital solution and physical parameters*

With the RVs in hand, we have performed an orbital solution for an SB1 binary using the method of Rauw et al. (2000), which is based on the Wolfe, Horak & Storer algorithm (Wolfe et al. 1967). The resulting parameters are given in Table 1. Note the small eccentricity justifying that the fit of the RV curve in Fig. 2 is almost a cosine. The orbital solution also gives the mass function

$$f(m) = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2} = 10.47 M_\odot \quad (1)$$

from which one can estimate the individual masses of each component (M_1 and M_2) if one uses in addition Kepler's third law

$$M_1 + M_2 = \frac{4\pi^2 r^3}{GP^2} \quad (2)$$

where r is the separation between the two stars and P the period. However, one needs an estimate of 1) the inclination and 2) the separation. As for the latter, the absence of plateau in the K band light-curve indicates that contact is achieved in the binary: as soon as the primary eclipse ends, the secondary eclipse starts. Hence, one can assume that r is simply the sum of the radii of the two components. The value of $a \sin i$ we find (and a itself, $\sin i$ being close to 1, see below) is similar to the stellar radius of LBVc stars derived by Najarro et al. (1997), so we assume $r = 2 \times a$. In that configuration, the two stars, which we know have similar K magnitude, have similar radii and rotate around each other, the center of mass being the contact point. To get an estimate of the inclination, we have used the software NIGHTFALL [6] to fit the light-curve (see result in Fig. 3). Assuming a similar effective temperature of 28000 K for both components (see Najarro et al. 1997) and a light ratio of one, we obtained a reasonable fit with an inclination $i \sim 70$ deg. Note that we had to adopt Roche lobe filling factors of 1.3 (the maximum allowed value in NIGHTFALL) to correctly reproduce the light-curve. If filling factors lower than one are used, the light-curve can not be reproduced correctly as the "peaks" are too broad (a problem encountered by DePoy et al. 2004). This confirms that contact is achieved and justifies our assumption that the separation is the sum of the stellar radii.

[6] software developed by R. Wichmann and freely available at the following URL http://www.hs.uni-hamburg.de/DE/Ins/Per/Wichmann/Nightfall.html

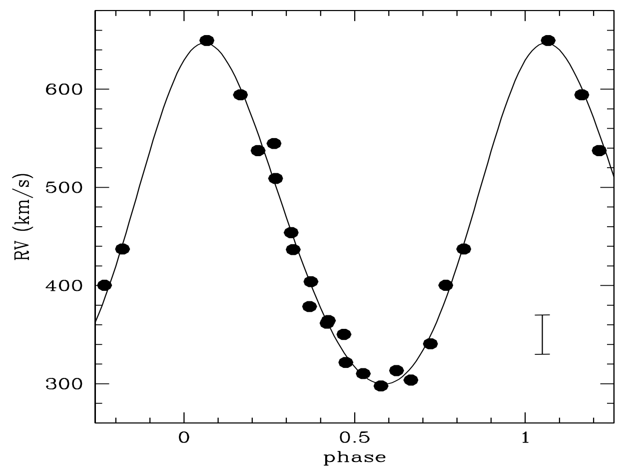

FIG. 2.— Radial velocity curve of IRS16SW together with the best orbital solution (for P = 19.45 days, solid line). The typical uncertainty on the radial velocity is ± 20 km s^{-1}. Parameters for the best fit solution are given in Table 1.

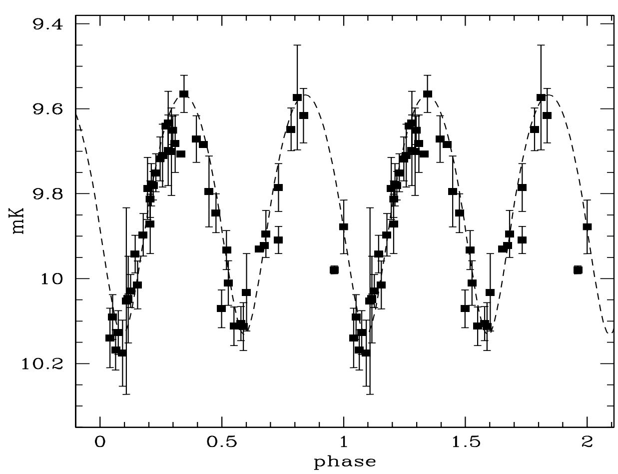

FIG. 3.— K band light-curve displayed for a period of 19.45 days, together with the best fit (dashed line). Data are from Ott et al. (1999). The two eclipses are similar, indicating that both components of the binary have the same K band magnitude. Note also the absence of plateau which suggests that contact is achieved.

TABLE 1
ORBITAL PARAMETERS - SEMI-MAJOR AXIS, ECCENTRICITY, SYSTEMIC VELOCITY, AMPLITUDE, LONGITUDE OF PERIASTRON - AS DERIVED FROM THE ANALYSIS OF THE RADIAL VELOCITY CURVE.

$asini$ [$R_\odot$]	66.4 ± 2.2
e	0.088 ± 0.023
v_0 [km s^{-1}]	459.5 ± 3.6
$K1$ [km s^{-1}]	173.8 ± 5.5
ω [deg]	334.0 ± 18.3

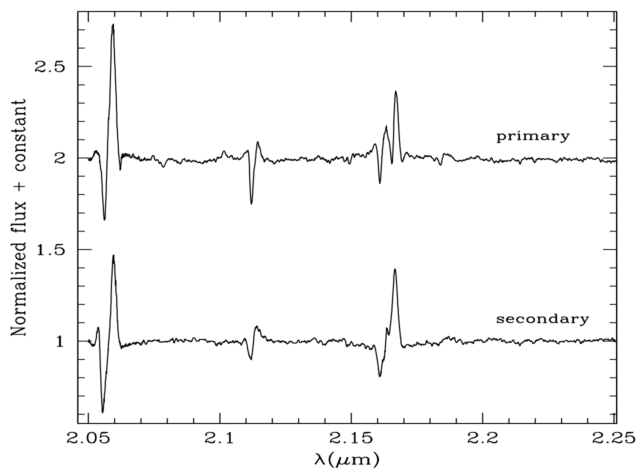

FIG. 4.— Spectra of the primary (top) and secondary (bottom) components of IRS16SW as obtained from the spectral disentangling analysis. These spectra should be interpreted with caution since they were obtained under several assumptions (see text).

Given the limitations on the light-curve fit and the complications in the physics of the star due to contact (mass transfer, departure from sphericity due to gravitational interaction, hot spot in interaction region), we stress that our estimate of the inclination is only indicative. It is however consistent with the value expected for an eclipsing binary. With $i \sim 70$ deg, and using Eq. 1 and 2, we finally derive $M_1 \sim M_2 \sim 50 M_\odot$.

3.3. *Spectral disentangling*

In order to get more insight into the properties of the components of IRS16SW, we have attempted to disentangle the spectra using the method of González & Levato (2006). In practice, the RVs of the primary are used to evaluate an average spectrum in the primary's rest frame. This provides an approximation of the primary spectrum which is then shifted back into the observer's frame and subtracted from the observed spectrum. The residual is composed of the secondary spectrum from which RVs can be estimated. The whole procedure is then re-started inverting the role of the two components, and is iterated until convergence.

Due to the limited number of spectral lines and S/N ratio of our spectra, no solution could be found leaving all parameters free. We therefore decided to freeze the primary RVs at their values determined above. Given the results of the orbital solution, we also decided to set the mass ratio to 1.0, and assumed that both components have the same systemic velocities. In that case, convergence could be achieved and the resulting spectra are shown in Fig. 4. These spectra should be interpreted with caution. Not only they were obtained under the assumption that the mass ratio is 1.0, but the procedure used also implies that the spectra are free of contamination by wind-wind collision or any other interaction in the contact region. With these restrictions in mind, the main qualitative conclusion we draw is that the spectra of both stars, and consequently their properties, are similar and typical of LBV candidates such as the Pistol star (Figer et al. 1999).

4. DISCUSSION

4.1. *Binary versus pulsating variable*

DePoy et al. (2004) argue that IRS16SW was a pulsating massive star based on the absence of second minimum in the light-curve and the difficulty to fit this light-curve in the binary scenario (but see Sect. 3.2). They compare the observed variation in K magnitude to the predictions of the dynamical models of Dorfi & Gautschy (2000) and conclude that there is a reasonable qualitative agreement. However, there are some quantitative discrepancies. First, the amplitude of the variation is much larger than predicted: although Dorfi & Gautschy (2000) do not compute K band photometry, one can estimate the variation in this band to be at most 0.2 mag (inspection of their Table 2 reveals that the amplitude of photometric variations decreases with wavelength and is $\lesssim 0.2$ mag in the I band), while we observe 0.55 mag. Second, the period we derive – 19.45 days – is larger than expected in the pulsating scenario (see Table 1 of Dorfi & Gautschy 2000).

Concerning spectroscopic changes, although in principle one can not completely rule out the possibility that they are due to motions of the atmosphere and fluctuations of the physical parameters ($T_{\rm eff}$, radius) due to pulsations (Dorfi & Gautschy 2000), the timescales are again not consistent: ~ 1 day for pulsations compared to 19.45 days observed. Besides, so far there are no theoretical predictions of spectroscopic changes caused by pulsations to which we could compare our observed spectra. The binary nature of IRS16SW is thus strongly favored.

The absence of secondary eclipse in the light-curve is explained by the similar K band magnitude of the two components. This is another indication that both stars are very similar. DePoy et al. (2004) report the presence of a variation in $H-K$ on a period of 9.725 days, $H-K$ being bluer when the system is brighter. A similar trend was observed in the optical photometry of the massive contact binary V606 Centauri (Lorenz et al. 1999). We interpret this as a sign of heating in the contact zone, making the spectral energy distribution in this region bluer. Massive binaries are indeed known to produce X-rays through colliding winds, and we might expect the same kind of interaction and heating around the contact region. Again, since this region is seen twice during an orbital revolution, an observed period half the true orbital period is naturally derived from the $H-K$ curve.

4.2. *Stellar evolution and the LBV phenomenon*

Whether or not all massive stars go through the LBV phase is still under debate. Langer et al. (1994) and Pasquali et al. (1997) argue that this is the case, while other observational (Crowther et al. 1995) and theoretical (Meynet & Maeder 2005) studies indicate that the most massive stars ($M \gtrsim 60 M_{\odot}$) may skip this phase. This is an important issue since although short, the LBV phase is crucial in the mass loss history, and consequently in the subsequent evolution, of massive stars. Recent studies by Smith & Owocki (2006) even claim that most of the mass of hot stars is lost during the LBV phase. Here, we provide an accurate measurement of the present mass of a candidate LBV, confirming that a star with an initial mass larger than 50 $M_{\odot}$ (and likely of the order 60-70 $M_{\odot}$) may become a LBV. This is a strong constraint for evolutionary models.

Of course, one could argue that the star's evolution was affected by binarity. However, inspection of the spectral morphology and physical properties (see Najarro et al. 1997) of IRS16SW and the other LBVc in the Galactic Center shows similarities. Our monitoring of IRS16SW also includes the other LBVc in the Galactic Center. Except for IRS16NE, none of these stars showed any spectroscopic variation, ruling out the possibility that they are close binaries. IRS16NE showed some RV fluctuations (see also Tanner et al. 2006), but so far we do not have enough data point to sample an hypothetical RV curve. Hence, the similarity between the spectrum of IRS16SW and those of the other single LBV candidates leads us to the conclusion that binarity has not (yet?) significantly affected the evolution of IRS16SW. Since the mass of the two components is similar, one can speculate that IRS16SW is composed of two stars initially equally massive that have so far evolved in parallel in a detached system, without influencing each other. They may have just entered the LBV phase during which contact was achieved due to their respective expansion. This event probably happened very recently (the LBV phase lasting $\sim 10^5 yr$) so that the general properties of both components have not yet been affected by mass transfer and binary evolution. Such a scenario is consistent with both stars displaying similar spectra (but see Sect. 3.3 for caution words).

Assuming that IRS16SW was not affected by binary evolution, the properties of the LBV candidate in IRS16SW can thus be used to constrain evolutionary models of single massive stars. In their recent models including rotation, Meynet & Maeder (2005) stressed that the LBV phase is not systematically reached above 45 $M_{\odot}$. Here, we have an example for which it is the case (under the assumption that IRS16SW will turn – or has already turned in the past – into a genuine LBV).

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