THE NATURE OF THE VARIABLE GALACTIC CENTER SOURCE IRS 16SW
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ABSTRACT
We report measurements of the light curve of the variable Galactic center source IRS 16SW. The light curve is not consistent with an eclipsing binary or any other obvious variable star. The source may be an example of a high-mass variable predicted theoretically but not observed previously.

Subject headings: Galaxy: center — stars: individual (IRS 16SW) — stars: variables: other

1. INTRODUCTION
The star cluster at the Galactic center (GC) is unique in the Milky Way. It is composed of a mixed population of young and old stars in a very dense cluster around the central supermassive black hole. Various efforts to study the members of this cluster have involved imaging and spectroscopic observations (e.g., Blum et al. 1996; Krabbe et al. 1995), all in the infrared because the extinction to the GC is \( A_V \approx 30 \) mag (Becklin & Neugebauer 1968). Tollestrup et al. (1989) and Blum et al. (1996) also discussed the variability of stars as probes of the stellar population content, although the data sets involved had sparse temporal sampling. More recently, Ott et al. (1999) used the results from 7 yr of observing (roughly 6–7 nights per year) to identify many variable stars in the GC, including the discovery that one of the sources very near the GC, IRS 16SW, is a short-period variable.

In 1999 we began a long-term project to monitor the GC. We obtained infrared images of the GC for many nights in subsequent observing seasons. The goals are to identify all the variable stars in the GC and use the statistics to better understand the star formation history of the region. The data collection for this project is ongoing, and we expect to produce the full results eventually. Here we report on the light curve of IRS 16SW from images taken during the 2001 observing campaign.

We find that IRS 16SW may be a representative of a new class of regularly pulsating massive stars. Pulsating stars are critical for the determination of the extragalactic distance scale, Cepheid variables in particular (see Gibson et al. 2000). However, even Cepheids are difficult to detect at large distances. Massive stars can have bolometric luminosities hundreds of times larger than Cepheids and can therefore be seen over much larger distances. The behavior of massive stars is intrinsically complex, however, so their use as standard candles has been limited (see Krabbe et al. 1995; Neugebauer 1968). Tollestrup et al. (1989) and Blum et al. (1996) reported by Blum et al. (1996). Intercomparison of 10 of these images was then used to provide the sky subtraction for each filter.

The final nightly images were trimmed to a size of 512 \( \times \) 512 pixels, providing a field of view of 112” centered approximately on the GC. Upon inspection, some of the images were found to be of poor quality, typically because of poor seeing, bad telescope focus or tracking, or excessive wind shake. Eighty-nine K images and 83 \( H \) images were 30 s exposures, and the individual \( K \) images, 10 s exposures. The groups of seven images required roughly 4 minutes at \( H \) and 2 minutes at \( K \) to obtain. Between the \( H \) and \( K \) images we acquired similar sequences of images of a sky position several degrees from the GC. The sets of images were flat-fielded using dome flats and then shifted and combined to create single \( H \) and \( K \) images for that night; a similarly processed sky image was then used to provide the sky subtraction for each filter.

2. OBSERVATIONS, DATA REDUCTION, AND RESULTS
Images of the GC in the \( H \) (1.65 \( \mu m \)) and \( K \) (2.2 \( \mu m \)) bands were obtained 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 a description of the instrument). On the CTIO/Yale 1 m telescope the ANDICAM’s infrared camera has a pixel scale of 0.22 pixel\(^{-1}\), which provides a total field of view of 225” on the 1024 \( \times \) 1024 HgCdTe array.

The first images for our 2001 observing campaign were obtained on UTC 2001 May 20 (HJD 2,452,049.5); additional images were obtained on every usable night through UTC 2001 November 2 (HJD 2,452,216.5). On each night, we acquired seven individual images of the GC, each slightly offset from the others, in each of the \( H \) and \( K \) filters. The individual \( H \) images were 30 s exposures, and the individual \( K \) images, 10 s exposures. The medians of seven images required roughly 4 minutes at \( H \) and 2 minutes at \( K \) to obtain. Between the \( H \) and \( K \) images we acquired similar sequences of images of a sky position several degrees from the GC. The sets of images were flat-fielded using dome flats and then shifted and combined to create single \( H \) and \( K \) images for that night; a similarly processed sky image was then used to provide the sky subtraction for each filter.

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The images of the GC at \( H \) and \( K \) are extremely crowded (roughly five bright sources within ~2” in the IRS 16 complex; see Ghez et al. 1998; Eckhart et al. 2002). Furthermore, the median seeing in our images is ~1.8” but ranges from a minimum of 0.94 to a maximum of 2.04. Therefore, simply performing aperture photometry on IRS 16SW does not produce an adequately accurate light curve. Instead, we used the ISIS image subtraction package (see Alard & Lupton 1998; Alard 2000) to analyze the images.

We used the ISIS package to combine four of the best-seeing images in each band into a template image, and then we subtracted the template from each individual image, after convolving the template to the seeing in each image. The resulting subtracted images allowed us to measure all variable sources in the observed field, including IRS 16SW.

We photometrically calibrated the light curves by comparing the brightness of IRS 16SW in the template image with the brightness of isolated stars in the frame. These stars varied by \( \leq 0.5\% \) over the course of the 2001 observing season; the brightnesses of these stars were assumed to be the same as reported by Blum et al. (1996). Intercomparison of 10 of these
stars suggests that the absolute calibration of the photometry is accurate to within ~10%. We note that Ott et al. (1999) find the mean $K$ brightness ($m_K$) of IRS 16SW to be ~9.61 mag; we find $m_K = 9.5 \pm 0.1$ mag. The relatively insignificant difference could be due to slight differences in the effective wavelength of the filters used in the two data sets, since IRS 16SW is very red. Our measurement is also consistent with previous high angular resolution measurements of $m_K$ (e.g., Simon et al. 1990; Simons et al. 1990; DePoy & Sharp 1991; Blum et al. 1996).

We find that the mean $H - K$ color of IRS 16SW is $2.6 \pm 0.15$ mag. Previous determinations of the $H - K$ color of IRS 16SW include $2.00 \pm 0.07$ mag (Blum et al. 1996), $2.05$ mag (Rieke et al. 1989), $2.1 \pm 0.3$ mag (Simons et al. 1990), $2.4$ mag (Krabbe et al. 1995), and $2.8 \pm 0.2$ (DePoy & Sharp 1991). Our measurement is generally consistent with these previous determinations, although it is somewhat redder than the most precise (e.g., Blum et al. 1996). The marginally significant (~4 $\sigma$) difference between our determination of the $H - K$ color of IRS 16SW and that of Blum et al. (1996) suggests that our $H$-band magnitudes may contain systematic uncertainties. Note that Blum et al. (1996) measured the $H - K$ color on a single night (1993 July 13), so the variability of the color of IRS 16SW (see below) does not account for the difference.

We searched for the periodic signal in the $H$ and $K$ light curves of IRS 16SW using the multiharmonic analysis of variances (ANOVA) period-search algorithm described by Schwarzenberg-Czerny (1996). We used a C-language implementation based on a program provided by C. Alard for this analysis. Two harmonics were required to get a good periodogram fit, giving a period of variability of 9.725 ± 0.005 days, consistent with that reported by Ott et al. (1999). The period found for each of the $H$ and $K$ light curves was consistent to within the stated uncertainty, and we see no evidence for higher frequency overtones. Figure 1 shows the phase-folded light curves at $H$ and $K$ for IRS 16SW.

We note that the shape of the light curve is similar to that found by Ott et al. (1999). There are some differences, however. In particular, our light curve shows a more continuous change in brightness than that of Ott et al. (1999); we see no evidence of any part of the light curve that remains constant for a substantial fraction of the phase.

Also shown in Figure 1 is the color change in IRS 16SW over the period of variation. The $H - K$ color of the source changes by a total of $0.16 \pm 0.03$ mag (exclusive of systematic calibration uncertainties). The source appears bluest ($H - K \approx 2.52$ mag) at maximum light and reddest ($H - K \approx 2.68$ mag) at minimum light.

3. DISCUSSION

The shape and period of the IRS 16SW light curve suggests that it is either an eclipsing binary star system or some variety of periodic variable star. Careful examination of the properties of the light curve, however, rules out most of the familiar classes of explanations. Below we review and discuss these possibilities and present evidence that IRS 16SW may represent a new class of regularly pulsating massive stars.

3.1. Well-known Pulsational Variables

Ott et al. (1999) presented the possibility that IRS 16SW is a Cepheid variable. They concluded that IRS 16SW was not likely a Cepheid on the basis of the light-curve shape and apparent brightness of the source at $K$. They also note that the spectrum of IRS 16SW from Krabbe et al. (1995) is not consistent with that expected from a Cepheid. Our data show that IRS 16SW changes color by ~0.18 mag ($H - K$) over the course of its light curve. This is also inconsistent with the behavior of Cepheids, which typically show less than 0.05 mag $H - K$ color change over their periods (see Welch et al. 1984). It therefore seems unlikely that IRS 16SW is a Cepheid variable.

Nonetheless, the shape of the IRS 16SW light curve is reminiscent of pulsating variable stars (i.e., a sharper rise to maximum light followed by a slower decline). One possibility is that IRS 16SW is a $\beta$ Cephei variable. These are high-mass stars (6–30 $M_\odot$) that pulsate because of the $\kappa$-mechanism caused by ion absorption peaked at $T \approx 2 \times 10^5$ K that excite fundamental mode oscillations (see Deng & Xiong 2001). Known $\beta$ Cephei variables are early B-type stars (except for HD 34656; Pijulski & Kolaczkowski 1998; Fullerton et al. 1991). This may be due to the very short length of time higher mass stars spend in the appropriate part of the Hertzsprung-Russell diagram or because the pulsations in higher mass stars are of very small amplitude and difficult to detect (Dziembowski & Pamyatankh 1993; Deng & Xiong 2001). Furthermore, observations of $\beta$ Cephei variables suggest that the photometric amplitude of the variation decreases with wavelength (Heynderickx et al. 1994). In addition, the periods of $\beta$ Cephei variables are typically less than 1 day. Both of these are not particularly consistent with observations of IRS 16SW, although there are no observations of this class of variables in the infrared or any modeling predicting their behavior. We are not aware of any other well-observed class of pulsating stars that have characteristics similar to IRS 16SW.

3.2. Eclipsing Binary Systems

IRS 16SW does not seem to be an eclipsing binary. If IRS 16SW is an eclipsing binary system, then the lack of any secondary eclipse requires that either one of the systems is invisible (and the period is ~9.725 days) or that both components have the same effective temperature (and the period is...
actually $2 \times 9.725 = 19.45$ days). However, we detect a color change over the period, which indicates that if there are two stars in the system then one is cooler than the other or both are detected. Logically, then, IRS 16SW cannot be an eclipsing binary system.

Ott et al. (1999) proposed that IRS 16SW is an eclipsing binary and described two possible scenarios. The first was a contact binary system with a high-mass primary dominating the total light from the system eclipsed by a lower mass companion in a 9.725 day orbit around the primary. In such a system, we would expect to see a relatively deep primary eclipse followed by a shallow secondary eclipse half an orbital phase later. This is not seen in our light curve (see Fig. 1) and so can be ruled out. The second scenario was of a contact binary composed of two equal-mass stars each contributing equally to the total light. Dividing the light equally between the stars gives them radii of $64 R_\odot$, implying minimum masses of $75 M_\odot$ each for two stars in contact given an orbital period of 19,450 days ($2 \times 9.725$ days).

We modeled the expected light curve for this equal-mass contact eclipsing binary system using a Wilson & Devinney model (Wilson & Devinney 1971; Wilson 1979, 1990; we used a 1998 version of the code generously provided by R. E. Wilson). The Wilson & Devinney model correctly accounts for all of the relevant physics in two stars sufficiently close together to be distorted by their mutual gravitational fields. For this calculation we used two equal-mass stars with $T_1 = T_2 = 24,400$ K and $R_1 = R_2 = 64 R_\odot$ in a contact binary system with a circular orbit of semimajor axis $a = 64 R_\odot$ and a period of $P = 19,450$ days. The temperature and radius were selected on the basis of models of IRS 16SW by Najarro et al. (1997) modified to account for the binarity of the source (as suggested by Ott et al. 1999). The code modeled the stars as in contact with and distorted by tides, using limb-darkening parameters typical of electron-scattering atmospheres expected in such high-mass, hot stars. An orbital inclination relative to the line of sight of $i = 65^\circ$ produces a double eclipse with a depth of 0.3 mag, matching the amplitude of variability seen in our $K$-band light curve shown in Figure 1 (note that if $i = 90^\circ$, the eclipse depth should be exactly 50% of the light, or 0.75 mag). We note that we did not attempt to "fit" our light curve (other than by attempting to match the observed amplitude of the light curve); rather, we generated the predicted light curve for the equal-mass contact binary system described. The model light curve is shown plotted over our observed light curve in Figure 2. This model is clearly a poor match to the observed light curve. Furthermore, if the two stars have the same mass and evolutionary state, then there should be no systemic color change over the period; as mentioned above, this is contrary to the observed color change. Therefore, we rule out the equal-mass contact binary scenario.

3.3. A Massive Regularly Pulsating Variable?

If we rule out that IRS 16SW is a known type of pulsating star or an eclipsing binary system, then it must represent a new class of variable object. This intriguing possibility is supported by recent work on internal models of massive stars. In particular, Dorfi & Gautschy (2000) found that linearly overstable pulsational modes can develop into regular variability in radiation hydrodynamic simulations of massive stars. In particular, for very high mass stars their models suggest that these modes can cause very regular cyclic brightness variability with light curves similar to those of classic pulsating variables. The models suggest that this variation is stable over reasonably long timescales.

The highest mass model presented by Dorfi & Gautschy (2000) is for a $60 M_\odot$, $L = 900,000 L_\odot$, $T_{\text{eff}} = 18,000$ K star (their model M60C). The model predicts a regular pulsation with $P = 4.086$ days and peak-to-peak bolometric brightness variation of 0.66 mag. The light curve looks qualitatively like the one we observe for IRS 16SW: a relatively steep rise followed by a somewhat slower fall. The model predicts no significant phase shift between different filter passbands of features in the light curves, which Dorfi & Gautschy (2000) attribute to low heat capacity in the most superficial stellar layers. Color changes are present, however, since the effective temperature of the star changes during the pulsations. These aspects of the model are also consistent with our observations of IRS 16SW. Note that Dorfi & Gautschy (2000) simulated this model’s pulsation for a timescale of more than 20 yr without seeing a change in the pulsational properties.

However, Dorfi & Gautschy (2000) modeled variations only in specific optical passbands ($UBVI$), and their highest mass model has a period less than one-half that of IRS 16SW. Their models show that the amplitude of variability decreases with wavelength throughout the optical, with the largest amplitudes in the ultraviolet. The amplitude of the M60C model in the $I$ band is $\sim 0.2$ mag, suggesting that the variations in the near-infrared would be much smaller than we observe in IRS 16SW. Furthermore, all their models with $M > 30 M_\odot$ show secondary maxima caused by shock waves in the atmospheres of the stars (a difference between the dynamical timescale of the atmosphere and the pulsational period causes collapsing layers to collide with already rerising deeper layers); we see no evidence for these secondary maxima in our IRS 16SW light curve.

1 Ott et al. reported minimum masses of greater than $150 M_\odot$ for this case, but it is clear that they inadvertently used an orbital period of 9,725 days instead of 19.45 days as required by an equal-mass/equal-radius eclipsing binary system in which the primary and secondary eclipses are identical.
4. CONCLUSIONS

Observations of the Galactic center region over roughly the entire 2001 observing season show that IRS 16SW is a periodic variable star, confirming the results of Ott et al. (1999). The period of the variation is 9.725 ± 0.005 days in both the $H$ and $K$ bands. This is the same period reported by Ott et al., demonstrating that IRS 16SW has a period that has been stable for at least the past ~10 yr. There is a change in the $H - K$ color of IRS 16SW over this period of ~0.16 mag.

The light-curve shape and color change over phase demonstrate that IRS 16SW is not an eclipsing variable star. Instead, the light curve is most similar to that of a periodic pulsating star. However, the amplitude and color of the light curve and the luminosity of IRS 16SW are inconsistent with any known type of pulsating variable.

The observations are very roughly consistent with the predictions for an unobserved class of periodically varying, high-mass stars made by Dorfi & Gautschy (2000). Although the measured light curve resembles the predictions, there were also serious differences (period, amplitude, etc.), so the intriguing possibility that IRS 16SW is the first of a new class of high-mass variable stars cannot be confirmed.

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