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LUNAR OCCULTATION OF THE GALACTIC CENTER AT 2.2 MICRONS

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ABSTRACT

Results of the lunar occultation of IRS 16 on 1986 September 11 are reported. Sixty percent of the observed flux in a 6″.5 beam comes from four discrete sources. Three sources are unresolved pointlike objects (< 0″.05) and are assumed to be individual stars. The fourth object is well resolved with a diameter of 0″.3 (0.01 pc). By timing the lunar occultation, we have identified this 9th mag object with IRS 16 NE. This blue object near the dynamical center may be a very compact cluster of stars and thus the true center of the Galaxy.

Subject headings: galaxies: The Galaxy — galaxies: nuclei — infrared: sources — occultations

I. INTRODUCTION

The central parsec of the Galactic center is known to contain a variety of different types of objects, including a possible black hole. Because of ~30 mag of visible extinction by dust, most of the studies of the center have been made at radio and infrared wavelengths. Studies of the stellar component have been made primarily in the region around 2 μm. Early high-resolution maps of the region showed both diffuse emission, presumably from unresolved stars, and a number of discrete sources (Becklin and Neugebauer 1975). The source IRS 16 lies close to the maximum of the diffuse emission and near the dynamical center, as confirmed by the high-resolution rotation curve observations of Serabyn and Lacy (1985). IRS 16 is also within a few arcseconds of the peculiar compact radio source Sgr A* (Brown and Lo 1982), whose nature has not been established; it has been suggested that it may be associated with a black hole in the Galactic center. Images of IRS 16 at 1″ angular resolution by Storey and Allen (1983, hereafter SA); Forrest, Pipher, and Stein (1986, hereafter FPS); Tollestrup, Capps, and Becklin (1988, hereafter TCB); Lacombe, Léna, and Rouan 1987, hereafter LLR); and Allen and Sanders (1986) show it to have a complex structure at 2.2 μm. Much higher angular resolution will be important to understand the nature of the sources. Lunar occultations can provide angular resolution two orders of magnitude finer than the present maps.

Lunar occultations of the Galactic center are rare phenomena; the previous series occurred in 1968–1970. That series was observed at radio frequencies (Sandqvist 1974) and showed that the continuum radio source Sgr A consists of at least two components now known as Sgr A East and Sgr A West. Infrared techniques at that time were insufficiently advanced to make occultation observations useful.

The sequence of occultations of the Galactic center by the Moon in 1986–1989 offers a rare opportunity to study the structure of IRS 16 on a scale of about 10 mas, corresponding to a scale of some 85 AU at an assumed distance of 8.5 kpc (Kerr and Lynden-Bell 1986). This *Letter* reports preliminary results from the first of these occultations, which was visible from the Canary Islands.

II. OBSERVATION

The observation of the occultation was made using the Leicester indium antimonide photometer mounted on the Isaac Newton Telescope. This photometer uses a 0.5 mm Cincinnati Electronics detector in conjunction with a capacitative feedback preamplifier similar to that described by Barton and Allen (1980). A simplified readout system employs a voltage-to-frequency converter feeding a digital counter system. The system was configured to take photometric readings every 20 ms, under which condition the output is background-noise–limited when observing the bright sky close to the Moon with the aperture needed for the observation. A microcomputer system was used to store up to 80 s worth of data in digital form, with an analog tape recorder and an analog oscillograph recorder as backups.

The Isaac Newton Telescope at the Observatorio de la Roque de los Muchachos on La Palma, Canary Islands, is operated by the Royal Greenwich Observatory. It has a mirror diameter of 2.5 m. The observations were made with a standard *K*-band filter (2.0–2.4 μm). At the time of the occultation, the zenith distance was 70°, and the transparency of the sky was very good. The aperture used for the observation had an angular diameter of 6″.5. This aperture size was chosen in order to take in the whole of IRS 16 as mapped at 1″ resolution by

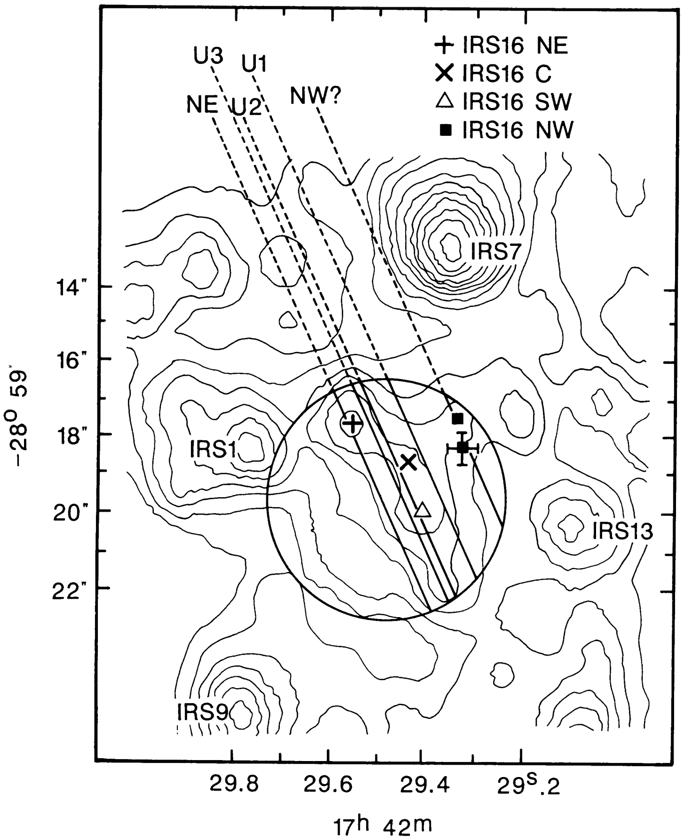

FIG. 1.—Map at 2.2 μm of FPS with the size and position of the observing aperture shown. The lines show the approximate position and angle of the Moon for each of the events discussed in the text. The exact angle and position of the Moon's limb as it covers a source cannot be determined because of the unknown lunar profile resulting from craters (see text). The symbol with error bars represents Sgr A*.

SA, FPS, and TCB, but to exclude the nearby bright sources IRS 7 and IRS 1. Positioning of the 6$''$.5 beam was achieved by offsetting 6$''$.35 south and 2$''$.0 east from the starlike source IRS 7. An off-axis guide star to the east of the center was used to check telescope tracking, which was accurate to about 0$''$.5. We conclude that the aperture was centered about 1$''$ south and 0$''$.5 east of the IRS 16 center at the time the occultation took place (see Fig. 1).

The approximate time of the occultation of IRS 16 was 22:23:20 UT on 1986 September 11. The event was an ingress of the source behind the dark limb at a position angle on the limb of the Moon of approximately 118° measured east from north. The event was digitally recorded from 40 s before this time to 30 s afterward; the relevant section of occultation data is shown in Figure 2*a*. The photometric system was calibrated on the star HD 166208, which was assumed to have a *K* magnitude of 7.11 (Elias *et al.* 1982).

To test the overall response of the system, an occultation of the star SAO 185635 was observed 2 hr before the Galactic center event; the resulting data are shown in Figure 2*b*. Significant smoothing of the basic Fresnel diffraction pattern was to be expected due to the 20 ms integration time. However, at least two diffraction fringes were visible, and the peak intensity was 1.3 times the steady-signal level. The *K* magnitude of the star was approximately 7.3.

III. ANALYSIS

The Moon's limb moved across the Galactic center at a rate of 0$''$.35 ± 0$''$.05 s^{-1}, and all of the radiation was covered in about 20 s. The error in the rate reflects the uncertainty in the angle of the lunar profile, which is discussed below. Inspection of Figure 2*a* shows that the limb of the Moon crossed the aperture between 22:23:10 and 22:23:30, with an error of 3 s in each time. The nominal lunar limb crossed the Galactic

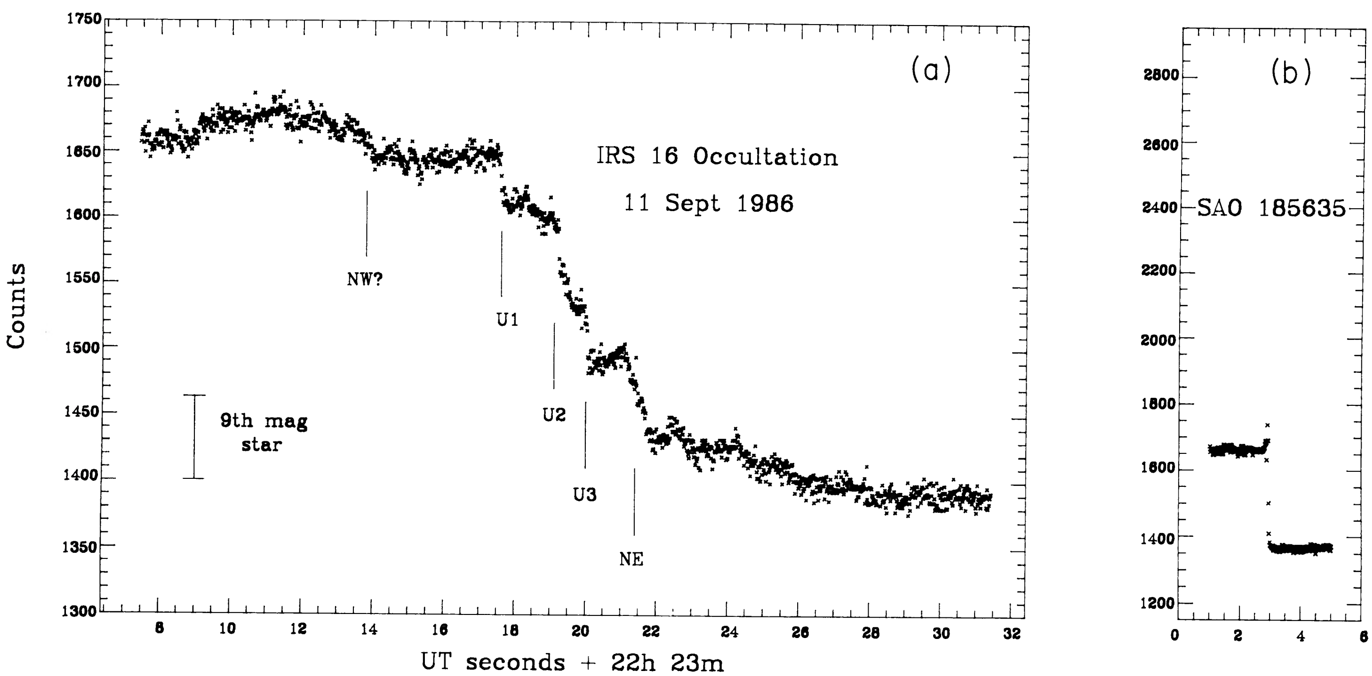

FIG. 2.—(*a*) The IRS 16 occultation record with discrete source positions shown. (*b*) The occultation of the star SAO 185635. The time scale is the same as in (*a*). The lunar rate is approximately 0$''$.3 s^{-1}. The *K* magnitude of the star is approximately 7.3.

center at an angle of 28° east of north (see Fig. 1); variations in the lunar profile angle caused by craters can be typically ±10° and are known to be as large as 30° (Evans and Edwards 1980).

There are four features in the occultation curve that stand out clearly. Three are sharp drops of a few data points (∼0.05 s); they are labeled U1, U2, and U3 and are thought to correspond to unresolved sources. A fourth feature is a steady drop in flux that occurs for about 1 s and is labeled NE; it is thought to result from a discrete extended source. There are several additional smaller features that are also seen. Examples are the drop in the flux marked NW and the drop in the flux between U2 and U3. Because of the low signal-to-noise ratio in these additional features, we will not discuss any of them except NW, which is very close to the nonthermal radio source (Brown, Johnston, and Lo 1981). By comparing the predicted path of the lunar limb across our aperture with the four available high-resolution images of IRS 16 (SA, FPS, TCB, and LLR), we tentatively identify the slightly extended source with IRS 16 NE. It is a common feature of all four maps and is the last major source to be occulted. Figure 1 shows schematically the order of the occultation events on the map of FPS. The three compact sources then have positions consistent with their lying within the feature described as the IRS 16 center and IRS 16 SW by SA, as the IRS 16 center and IRS 16 SW(1) and IRS 16 SW(2) by TCB, and as IRS 16 CE, IRS 16 CW, and IRS 16 SW by LLR. The first compact source (U1) is probably associated with a component of IRS 16 center for any reasonable angle of the lunar profile. There is insufficient information to be able to locate without ambiguity the unresolved sources along the NNE-SSW line. This is especially true since the angle of the lunar profile may be different for various sources (1″ = 2 km on the Moon).

Since the occultation was observed, we have obtained from L. Morrison (1986) accurate lunar limb positions that take into account the variable angular diameter and limb profile of the Moon. The occultation time for IRS 16 NE, at an assumed 1950.0 position of $17^h42^m29^s.55$, $-28°59'17''.6$ (average of positions given by SA and TCB) is calculated to be $22^h23^m22^s.4$ UT with a probable error of ∼1.0 s. This time is within the error of the observation of the slightly extended source between $22^h23^m21^s.0$ and $22^h23^m21^s.7$ and supports our identification of it with IRS 16 NE. Occultation times for the sources IRS 16 C and IRS 16 SW have also been calculated. Unfortunately, the possible error of 1.0 s in these calculations, coupled with possible position errors of the sources and their approximate alignment along the limb of the Moon, make identification of the three unresolved sources with IRS 16 C and IRS 16 SW ambiguous. It is interesting to note that the Watts charts used by Morrison give a limb angle of 35° in the northern part of the aperture and 28° in the southern part.

Early in the occultation there is a probable source denoted as IRS 16 NW; this identification is based on timing relative to the source IRS 16 NE (calculated occultation time for IRS 16 NW, position $17^h42^m29^s.32$, $-28°59'17''.5$ from FPS and TCB is $22^h23^m12^s.8$), and on the expected signal strength. The detection of IRS 16 NW should be regarded as very tentative, because in the 25 s worth of data prior to the occultation two dips in the signal were seen, one of two-thirds the depth and one of nearly twice the depth of IRS 16 NW. These features we attribute to seeing and tracking noise (after the occultation, the noise was Gaussian). There is therefore a possibility that the IRS 16 NW feature is an artifact of seeing and tracking noise. Overall, taking into account the fact that the signal did not return to its previous higher level, as occurred after each of the "dips," IRS 16 NW was detected with 70% confidence.

The sections of data immediately surrounding each of the discrete sources labeled in Figure 2 have been carefully examined. The lack of a definite Fresnel pattern does not mean that the sources are resolved, because of the finite sampling interval and limited signal-to-noise ratio of the data. Chi-squared fits to the expected Fresnel fringe pattern for a range of source sizes (Simons 1986) in the case of the three compact sources do not converge upon a single set of source sizes with statistically unique χ^2 values owing to the limited signal-to-noise ratio. We conclude on the basis of the sharp cutoffs visible in Figure 2 that the three compact sources are probably unresolved in this observation, with angular sizes $<0''.05$.

Fluxes and magnitudes of each component have been estimated from the occultation curves and are given in Table 1. The uncertainties in the fluxes are large and due to the signal-to-noise ratio and the uncertain background emission. The results are subjective, and we estimate the error to be ±20%.

There is definite evidence on the occultation record for the presence of diffuse emission within the observing aperture. The difference between the flux detected at the beginning of the occultation and that detected at the end is 820 mJy, equivalent to one 7.2 mag star in the K band. By summing the contributions from the identified discrete sources, 480 mJy is obtained, so that the diffuse flux within the aperture amounts to 340 mJy. In principle, the occultation profile with the discrete sources subtracted should give additional information on the distribution of extended emission. In practice, conclusions drawn from an analysis of these data would be unreliable because of the low-frequency variations caused by changes in the background flux from the dark side of the Moon and from noise caused by seeing and tracking variations.

IV. DISCUSSION

The high level of source confusion in the Galactic center makes accurate photometry of the IRS 16 components difficult. The occultation measurements allow the brightness of the pointlike components to be determined relatively free from contamination by extended emission. Combined with the 1 μm CCD photometry of Henry, DePoy, and Becklin (1984), we can obtain limits on the colors of the components. To do this without unique identification of the sources in the center/southwest complex, we have assumed that neither C nor SW is brighter than the sum of the two brighter unresolved com-

TABLE 1

SOURCE MAGNITUDES OF COMPONENTS OF IRS 16 AND IRS 12

Component	K (mag)	Flux (mJy)	[1 μm] (mag)	[1 μm] − K (mag)	$M(K)$[a] (mag)
IRS 16 NE	8.9	170 ± 40	19.5	10.6	−8.4
IRS 16 U1	9.5	100 ± 20	...	...	−7.8
IRS 16 U2	9.5	100 ± 20	...	...	−7.8
IRS 16 U3	9.4	110 ± 20	...	...	−7.9
Center[b]	>8.7	...	20.6	<11.9	...
Southwest[b]	>8.7	...	20.8	<12.1	...
IRS 12[c]	8.8	...	>22.3	>13.5	−8.5

[a] Assumes extinction at K is $A_K = 2.7$ mag.

[b] The colors of the center and southwest have been calculated assuming a K contribution to each of at least U1 and U2 for center and U2 and U3 for southwest.

[c] The K and [1 μm] magnitudes of IRS 12 as estimated by TCB.

ponents. Table 1 lists K, [1 μm], and ([1 μm] $-$ K) magnitudes for the components of IRS 16 and for IRS 12. The latter is given to illustrate the color of a typical Galactic center source. (Note that TCB have recently shown that IRS 12 is double and that there exists only a 1 μm limit on the red giant.) It can be seen that all the IRS 16 sources are at least 1.5 mag bluer in the [1 μm] $-$ K color than the late-type star IRS 12. This could result from less interstellar reddening to IRS 16 or because IRS 16 is intrinsically less red than IRS 12. Support for the latter explanation comes from the observation that the IRS 16 components have very weak CO band strengths; early-type stars with blue [1 μm] $-$ K colors do not show CO absorption.

a) The Three Unresolved Sources

A close inspection of the image of the Galactic center by TCB indicates that IRS 16 SW is probably double, so that there are three sources in the IRS 16 C/SW region; the image by LLR resolves the IRS 16 center into two sources, so that again there are three sources in IRS 16 C/SW. We have labeled the three unresolved sources corresponding to the IRS 16 C/S complex IRS 16 U1, U2, and U3, but we are unable to assign them uniquely within the C/SW complex. They are probably stars with absolute K magnitudes of about -7.8. As noted above, the IRS 16 components have weak CO absorption and have relatively blue colors. Combining the three observations suggests that the objects are individual early-type supergiant stars. If they are the ionizing sources for the central region, then they are B-type supergiants (Lacy, Townes, and Hollenbach 1982). Because the lifetime of an early-type supergiant is so short (10^4 yr), the likelihood of having three objects in this evolutionary stage seems very small. The nature of these three sources at this time is unknown.
unknown.

b) IRS 16 NE

The most interesting aspect of this source is the 0."3 angular extent. At the distance of the Galactic center, this corresponds to a linear size of 0.012 pc. The source also lies closest to the kinematic center as determined from the ionized gas (Serabyn *et al.* 1988). IRS 16 NE appears to be the bluest component of IRS 16, and weak hydrogen line emission is associated with it (Storey and Allen 1983). However, the extended emission is not likely to originate from the ionized gas because the expected continuum emission is much too weak and the overall spectrum is too blue. Most likely, the radiation observed at 2.2 μm is from stars. The angular size of the source makes it far too compact to be compared with a Galactic cluster that has a scale of several parsecs. Allowing for an extinction correction of $A_K = 2.7$ mag, the integrated magnitude would be $K = 6.2$ mag. Very approximately, this is 300 times brighter than the center of a "collapsed-core" globular cluster (such as M15) would appear over the same scale. A mass of $10^5\ M_\odot$ would be deduced if the mass-to-light ratio were similar to that of a globular cluster at 2.2 μm, but the relatively blue color makes identification with such a late-type population unlikely. A bluer color and lower mass would be required if the source were a cluster of young supergiants. How such a cluster would form and stay together is an interesting question.

We conclude that the nature of IRS 16 NE is unknown, but the present result that it is extended on a scale of 0.01 pc together with other known properties suggests that it may be the most interesting object seen at 2 μm in the center of the Milky Way.

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