THE ASTROPHYSICAL JOURNAL, 344: L5–L8, 1989 September 1

IONIZATION OF THE MASS-LOSS WIND OF THE M SUPERGIANT IRS 7 BY THE ULTRAVIOLET FLUX IN THE GALACTIC CENTER

G. H. RIEKE[1] AND M. J. RIEKE[1]
Steward Observatory, University of Arizona
Received 1988 August 2; accepted 1989 June 22

ABSTRACT

We have detected the Brα hydrogen recombination line from the M supergiant IRS 7 in the Galactic center. The line strength appears to be stronger than expected for normal stellar processes. If the star lies within 0.6 pc of the Galactic center, the ionization can be explained as the effect of the ambient field of ultraviolet photons on the mass-loss wind of the star. This model requires that massive stars formed in the Galactic center in the last 10^7 yr; it is then likely that they account for a significant portion of the luminosity and excitation of the central parsec of the Galaxy.

Subject headings: galaxies: The Galaxy — stars: mass loss — stars: supergiants

I. INTRODUCTION

The central parsec of the Galaxy is the site of a bewildering display of infrared and radio emission (e.g., Genzel and Townes 1987). Although there is no obvious single candidate as the source of this activity, some form of central engine would be attractive in view of our hypotheses about other galaxies. The structure in the infrared might suggest a central engine in the form of a cluster of exotic objects. Alternatively, recent star formation may make a major contribution, as indicated by the detection of one or more red supergiant stars that lie close to the Galactic center on the sky (Lebofsky, Rieke, and Tokunaga 1982). The outstanding example is IRS 7, which lies at 0.3 pc projected distance from Sgr A* and is reliably classified from its spectrum to be an M1–M2 supergiant (Lebofsky, Rieke, and Tokunaga 1982; Sellgren *et al.* 1987).

The attribution of recent star formation to the Galactic center would not be necessary if IRS 7 (and perhaps other stars) are foreground or background objects that are projected onto the region from a substantial distance. Such a hypothesis seems improbable from a statistical point of view, but it is attractive because the current conditions in the Galactic center are dramatically different from those believed to foster star formation. This issue could be settled if some peculiarity were found in IRS 7 that required the environment of the Galactic center for its explanation. We have therefore examined whether the ambient ultraviolet photon field in the Galactic center ionizes some of the gas associated with the star.

II. OBSERVATIONS

The spectra reported here were measured on the CTIO 4 m telescope with the facility infrared spectrometer. The entrance aperture was set to 2″.5. A 210 lines mm^{-1} grating gave a resolution of 926, or 324 km s^{-1}, at the wavelength of the Brα line, 4.05 μm. In our measurements, the grating tilt was incremented 6 times by one-sixth of the resolution element. The spectrometer has eight detectors, so a complete spectrum contains 48 measurements spaced at 54 km s^{-1}. Relative velocities can be derived from data of this type with an rms accuracy of about 20 km s^{-1} (Rieke and Rieke 1988), so long as an astronomical source close on the sky is used as a calibrator.

In addition to the eight detectors for spectral measurement, the instrument diverts about 15% of the undispersed light to a ninth detector that gives a measure of the effects on the signal of seeing fluctuations, guiding errors, and changes in atmospheric transmission. The signal from this monitor channel allows measurements from different grating settings to be normalized to provide a consistent spectrum. This channel was used with a broad-band *K* (2.2 μm) filter.

We believe that all the data in the final spectrum of IRS 7 apply to a region no more than 2″ in radius centered on the star. In addition to use of a 2″.5 entrance aperture, a number of additional precautions ensured that this would be the case. The observations were made on the night of 1988 April 29, which was photometric and with seeing of ∼1″. The telescope was offset from nearby stars to the position of IRS 7, and the signal in the monitor channel was carefully peaked. Because IRS 7 is by far the brightest compact object in the Galactic center at 2.2 μm, this procedure guaranteed that we were pointed accurately at it. Once the signal had been peaked, the position of a field star was marked on the acquisition TV monitor and used for subsequent guiding. During spectral acquisition, all data points were rejected in which the monitor channel signal (at 2.2 μm) fell below 85% of its maximum intensity. Thus, data were systematically discarded in which seeing fluctuations or guiding errors created a possibility of significant contamination from surrounding regions. Approximately 20% of the data were rejected for this cause. On the night of these observations, a malfunction in the telescope caused it to lose track dramatically occasionally but otherwise to behave normally; most of the rejected data were from periods when the tracking was bad.

From infrared and radio maps, it was determined that areas free of Brα emission lay 30″ to the north and south of IRS 7, so the throw of the chopping secondary was set to this value. Data were obtained in a conventional mode, where the telescope was wobbled periodically so the IRS 7 spectrum was measured alternately with reference to each of these areas.

Four additional sources were measured for calibration purposes. The Brα line in IRS 1 was used to calibrate the velocity scale of the instrument and to determine the effective

[1] Visiting Astronomer, Cerro Tololo Interamerican Observatory, National Optical Astronomy Observatories, operated by the Associated Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

resolution. The radial velocity of IRS 1 was taken to be +20 km s^{-1} and its line width to be negligible compared with our resolution (Serabyn 1984). BS 6693, an M1 supergiant near the Galactic center on the sky, was used as a comparison standard that would include any spectral features that lie near Brα in the spectrum of IRS 7. X Sgr was used as a hotter calibration star to assist in identifying any absorptions in the terrestrial atmosphere. These sources plus IRS 7 were measured in sequence, with this sequence repeated 4 times. The results reported here are averages of these four measurements of each source. Finally, through the kind cooperation of D. Terndrup, we measured the spectrum of the M2 supergiant, NGC 4755-D (Feast 1963).

Errors were estimated from the repeatability of the measurements. Nominally, the errors for IRS 7 were less than <0.5% per spectral point. BS 6693 and X Sgr were measured to nominal accuracies roughly 3 times higher, and IRS 1 to an accuracy of about 1% rms in the strong part of the Brα line. All measurements were made through less than 1.3 air masses.

III. DATA REDUCTION

Data reduction was carried out in the Lotus 1-2-3 environment. First, we examined the corrections for atmospheric transmission and instrumental response. X Sgr has a significant Brα absorption feature; therefore, the atmospheric transmission was determined by comparing the instrumental response function with artificial spectra generated by adding the X Sgr and IRS 1 spectra in various relative amounts. In these test spectra, the Brα emission from IRS 1 allows the filling in of the absorption in X Sgr to create a featureless continuum. It was found possible to reproduce the instrumental response to within 0.3% rms with these composite spectra, indicating that there were no significant atmospheric absorptions within the range of our spectra. Thus, all spectra were corrected for instrumental response alone.

The dominant feature in the spectra of IRS 7 and both of the other supergiants is the absorption bandhead at 4.043 μm due to the 3–1 transition in SiO (Cudaback, Gaustad, and Knacke 1971; Beer, Lambert, and Sneden 1974). To remove this feature, we first dereddened the spectrum of IRS 7 for an absorption equivalent to $A_v = 37$ and the extinction curve in Rieke, Rieke, and Paul (1988). Next, the spectrum of BS 6693 was blueshifted by 108 km s^{-1} to bring it to the same radial velocity as IRS 7 (Abt and Biggs 1972; Sellgren *et al.* 1987; Rieke and Rieke 1988). The strength of the absorption band was then adjusted to give the minimum residuals between the two stars for the spectra outside ± 500 km s^{-1} of the rest wavelength of Brα. Satisfactory agreement was obtained after adjusting the overall normalization of the spectra to account for the apparent brightness difference between the stars and adding a neutral component to BS 6693 accounting for 33% of its emission. This second parameter is the simplest model that allows adjustment of the strength of the absorption feature.

Comparison of the spectra of the two stars revealed an unexpected problem: there was an absorption feature in IRS 7 just to the red of the Brα rest wavelength and a weak emission just to the blue of this wavelength. Since the absorption was narrower than the instrumental resolution, it was not a true feature. However, it could arise from redshifted Brα emission in one or both of the reference beams combined with blueshifted Brα emission in the beam on IRS 7. Detailed modeling with the instrumental line profile measured on IRS 1 confirmed the viability of this hypothesis, and an examination of the data showed that the redshifted emission lay in the southern reference beam. The half of the IRS 7 data that used this reference beam was therefore rejected for all the following analysis. The steps described in the preceding paragraph were repeated with the remaining data, with the result displayed in Figure 1.

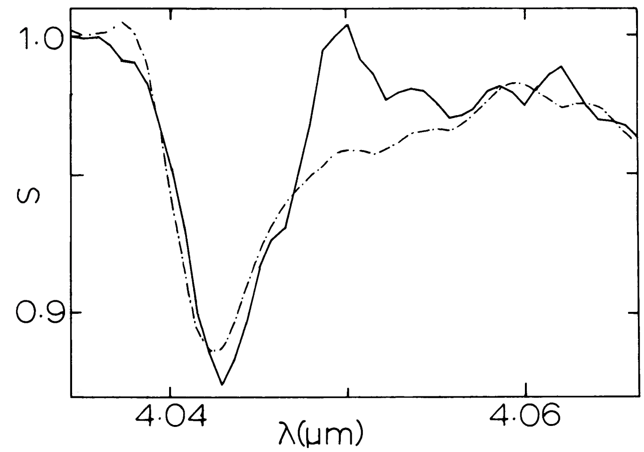

FIG. 1.—Spectra of Galactic center IRS 7 (*solid line*) and the M supergiant BS 6693 (*dash-dot line*). Both spectra have been normalized to a continuum strength of 1.0. The absorption bandhead is the 3–1 transition of SiO; a neutral component has been added to the spectrum of BS 6693 to bring the absorption depth into agreement with that for IRS 7.

The modified BS 6693 spectrum was subtracted from IRS 7 to show the excess emission of IRS 7 more clearly as in Figure 2. The strength of the emission line was calibrated from its equivalent width and photometry of IRS 7 (Rieke, Telesco, and Harper 1978; Becklin *et al.* 1978).

IV. DISCUSSION

a) Association of the Brα Emission with IRS 7

Further analysis examined whether the emission feature at the position of IRS 7 arises from the star or from an unrelated component of the interstellar gas. Serabyn (1984) shows an extensive set of measurements of the [Ne II] line from the interstellar gas. Some of these measurements are compared with Brα observations by Wade *et al.* (1987) in Table 1. One of Serabyn's measurements is with a 6″ beam centered on IRS 7. This measurement was corrected to a predicted Brα line strength in three steps. First, the [Ne II] strength was corrected to our 2″.5 beam according to the ratio of beam areas. Second,

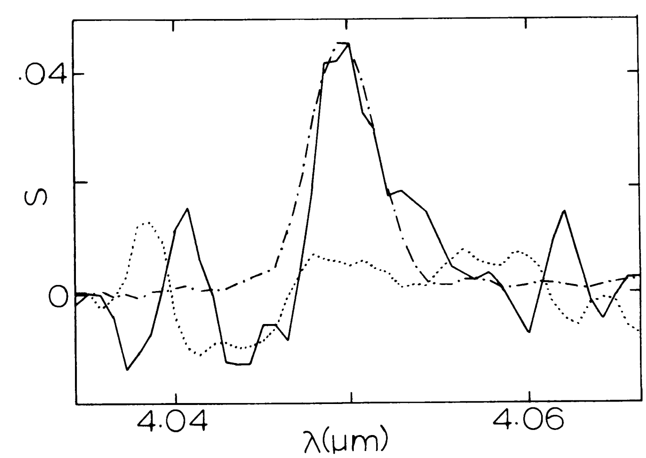

FIG. 2.—Difference between spectra of IRS 7 and BS 6693 (*solid line*). For comparison, the instrumental line profile is indicated as measured on IRS 1 (*dash-dot line*), as are the residuals in the difference between BS 6693 and another M supergiant, NGC 4755-D (*dotted line*).

TABLE 1

Brα AND [Ne II] LINE STRENGTHS

Source (IRS)	Brα (10^{-19} W cm^{-2})	[Ne II] (10^{-19} W cm^{-2})	[Ne II]/Brα
1	8.5	180	21
4	3.3	90	27
5	4.4	65	15
6	6.8	60	9
9	6.6	70	11
Average			17
7[a]	0.09	0.6	7

[a] Assuming that the [Ne II] emission is uniformly distributed over the 6″ beam used by Serabyn 1984.

the Brα strength associated with this line was determined assuming that the same ratio held for Brα/[Ne II] as is seen for IRS 1. Third, the predicted Brα line was smoothed from the resolution in Serabyn (1984)—48 km s^{-1}—to the resolution of our data. The results of these calculations are shown in Figure 3. They imply that the red wing on the IRS 7 emission feature arises from the interstellar cloud detected by Serabyn (1984). As shown in the figure, subtracting this component leaves an unresolved emission line at a radial velocity of -120 ± 40 km s^{-1}, in agreement with the stellar velocity of -128 km s^{-1} as determined from this star's CO absorption bands (Sellgren *et al.* 1987; Rieke and Rieke 1988). The strength of this feature is entered in Table 1. It is relatively weak in Serabyn's [Ne II] data, which could result if the emitting gas is strongly concentrated in our smaller beam, or if the emission arises in gas at high enough density that [Ne II] is partially deexcited.

Because of the complexity of the process leading to Figure 3, we point out that virtually every step utilized parameters from other observations. The only arbitrary parameter was the strength of the featureless continuum added to the spectrum of BS 6693 to bring its SiO absorption strength into agreement with that for IRS 7. All other velocities, line strengths, etc., were used as fixed parameters. A further test of the uncertainties was performed by reducing the spectrum of NGC 4755-D against that of BS 6693 using the same procedures as for IRS 7. As shown in Figure 2, the residuals from this process had a peak-to-peak amplitude of 1.3%, similar to those for IRS 7 away from the Brα line.

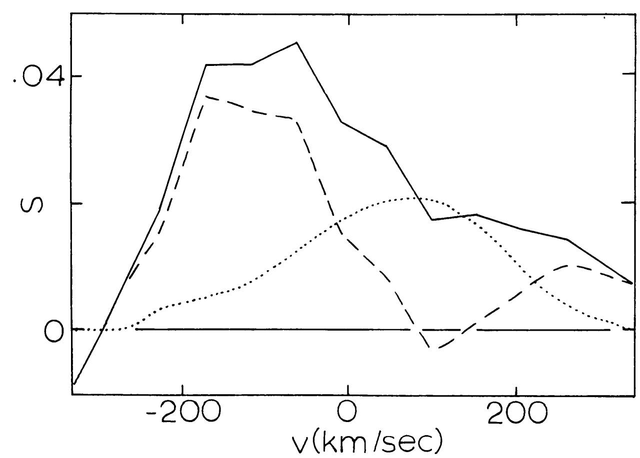

FIG. 3.—Brα emission from IRS 7. The solid line shows the total excess emission near the wavelength of Brα from Fig. 2. The dotted line is an estimate of the Brα that would accompany the extended cloud of [Ne II] emission in this region. The dashed line is the difference, an estimate of the Brα line that is associated with IRS 7.

Thus, there are at least two and possibly three reasons for associating the -120 km s^{-1} Brα emission component with IRS 7: (1) It is spatially coincident with the star to within 2″; (2) it is at the same radial velocity to within the measurement errors of ± 40 km s^{-1}; and (3) it may arise partially in gas of high enough density to deexcite [Ne II]. Subsequent to the above analysis, we learned that Yusef-Zadeh, Ekers, and Morris (1988) have detected a compact radio source centered on IRS 7, from which they arrive at very similar conclusions.

b) *Excitation of the Brα Line*

The derived Brα line strength, corrected for reddening according to the extinction law of Rieke, Rieke, and Paul (1988) with $R = A_v/E_{B-V} = 3.09$, is $\sim 4 \times 10^{-13}$ ergs cm^{-2} s^{-1}. The uncertainties in absolute line strengths are much larger than the ones in relative strengths used in the preceding discussion. For example, the 2 σ uncertainty in R (Rieke and Lebofsky 1985) corresponds to an uncertainty of a factor of 2 in the line strength. Our measurement is also subject to modeling and measurement uncertainties; in absolute terms, we can conclude only that the line is somewhat stronger than 10^{-13} ergs cm^{-2} s^{-1}.

Can the line in IRS 7 be attributed to normal stellar processes? Ionized hydrogen is frequently excited by shocks in highly variable or pulsating cool stars. However, IRS 7 has been observed for 20 yr and is apparently not strongly variable (e.g., Becklin and Neugebauer 1968, 1975; Becklin *et al.* 1978; Bailey, Hough, and Axon 1984; our unpublished data through 1988). The two other early M giants observed by us do not have similar emission, nor does α Ori (Beer, Lambert, and Sneden 1974). The equivalent width in Hα to accompany the Brα can be estimated to be ≥1 Å, which would be exceptionally large for weakly variable M supergiants.

Could the Brα emission in IRS 7 result from the environment within the Galactic center? The ionization could arise from the high ambient density of ultraviolet photons that impinges on the atmosphere of any star in this region. Models of this type have been proposed for the broad emission lines in active galactic nuclei (e.g., Mathews 1983). In the Galactic center, the ionizing photon production must be $\sim 10^{51}$ photons s^{-1}, assuming a single source or sources that are spatially concentrated (Lacy *et al.* 1980). For this flux, Mathews's formalism shows that the expected line is much weaker than observed.

However, stars similar to IRS 7 typically are undergoing significant mass loss. The increase in extinction centered on IRS 7 (e.g., Rieke, Rieke, and Paul 1988) suggests that not only is the star experiencing mass loss, but the level is relatively large. We have considered whether the Brα emission arises through ionization of this mass-loss wind. The wind is assumed to generate a shell of interstellar gas with an r^{-2} dependence of density that fills our 2″.5 diameter beam. We have taken all the ionizing flux to arise in a single source and have examined the effects of this source using a simple inverted–Strömgren sphere approach. With these assumptions, the predicted line intensity depends on only two parameters, M_5/v_{10} and d^2/F_{51}, where M_5 is the rate of mass loss (expressed in units of 10^{-5} $M_\odot$ yr^{-1}), v_{10} is the velocity of the escaping mass (expressed in units of 10 km s^{-1}), F_{51} is the UV flux (in units of 10^{51} photons s^{-1}), and d is the distance from the source of this flux (in pc). For nearby early M supergiants, typically $M_5 \sim 0.4$ and $v_{10} \sim 1$ (Goldberg 1985).

If F_{51} is fixed at 1, it was found that Brα line strengths $\geq 1 \times 10^{-13}$ ergs s^{-1} cm^{-2} with $d = 0.3$ pc required

$M_5/v_{10} \geq 2$; with $d = 0.6$ pc, $M_5/v_{10} \geq 3$; and with $d = 1.0$ pc, $M_5/v_{10} \geq 5$. Taking 0.7 as a plausible lower limit for v_{10}, the three cases correspond to values of M_5, respectively, of 1.5, 2, and 3.5. Even allowing for the evidence for a relatively thick shell around IRS 7, the latter value is uncomfortably high; it appears that our measurement places the star within about 0.6 pc of the source of ionization.

Alternate models for the ionizing source (e.g., having the ionization arise from many sources distributed through the region) can modify these conclusions slightly, but so long as the ionizing photons arise within the central parsec, it appears that IRS 7 must also lie very close to this region.

c) *IRS 7 and the Nature of the Galactic Center*

Given that IRS 7 lies within the Galactic center, its luminosity is remarkable—$M_{\rm bol} = -9.4$ for a distance to the Galactic center of 8 kpc. There may be a second extremely luminous late-type star in the same region, IRS 3. This source lies 4″ to the SW of IRS 7. It has $M_{\rm bol} = -8$ and is compact and heavily dust-embedded, with a strong intrinsic silicate absorption feature (e.g., Aitken *et al.* 1986). Its color temperature between 10 and 20 μm is 230–300 K (depending on the extinction law adopted). These properties are similar to those of the most luminous OH/IR stars (Jones 1987) and strongly suggest that IRS 3 is a star undergoing a very high rate of mass loss. OH emission might be expected from this object but is not detected (Winnberg *et al.* 1985). OH masers lie in the outer parts of mass-loss shells (Herman and Habing 1987), in the region that is ionized in IRS 7, according to our models. It is interesting to speculate that the ambient UV field in the Galactic center is suppressing the OH emission of IRS 3 by disassociation of the OH radical.

The luminosities of both of these objects are well in excess of the maximum for asymptotic giant branch stars (Jones 1987) and require them to be true supergiants with progenitor masses larger than $\sim 8\ M_\odot$. Uncertainties in late stellar evolution make it impossible to assign precise progenitor masses, but the extreme luminosity of IRS 7 suggests a progenitor mass $\geq 30\ M_\odot$. Such objects have extremely short lifetimes; the stars under discussion must have formed during the past 10^7 yr. The dynamical settling time scale is at least an order of magnitude larger than the age of these stars (Lebofsky, Rieke, and Tokunaga 1982), so they must have formed in or near the Galactic center.

Because current conditions in this region do not appear to be conducive to star formation, it is possible that IRS 3 and 7 have very different histories than other, similar stars. However, in a conventional picture there would be approximately 11 blue main-sequence stars of similar luminosity for every red supergiant (Humphreys 1978). These main-sequence stars would account for a luminosity of about $7 \times 10^6\ L_\odot$, a significant portion of the total from the region. This luminosity estimate is a lower limit because both IRS 3 and IRS 7 are at very late stages of evolution; additional red supergiants of slightly earlier spectral type than IRS 7 may not have been identified yet.

It appears that the central parsec of the galaxy contains a large number of sources of excitation, both the many components of IRS 16 (e.g., IRS 16 NE, C, NW, and S), and the cores of a number of 10 μm sources, such as IRS 1, 9, and 13 (Rieke, Rieke, and Paul 1988). Although the detailed properties of these objects do not appear to be as expected for single, luminous stars (Allen and Sanders 1986; Rieke, Rieke, and Paul 1988), their prevalence is generally consistent with the idea that hot stars account for much of the energetics of the region.

V. CONCLUSION

We have detected Brα emission from the red supergiant IRS 7 that lies on the sky within 0.3 pc of the Galactic center. If the star is within $\sim$0.6 pc of the ultraviolet source, the strength of this line can arise from the ionization by the ambient UV flux in the Galactic center. It is possible that the ionizing field also suppresses the OH emission from a second very luminous but dust-embedded star in the Galactic center, IRS 3. Given the extreme conditions in this region, it is not clear that these stars have evolved to their present state in a normal fashion; however, if they have, one would expect a population of hot, blue stars that could account for a significant portion of the overall excitation and luminosity of the Galactic center.

We are indebted to Brooke Gregory for his continued excellent support of the CTIO infrared spectrometer. We also thank Don Terndrup for permitting us to obtain the spectrum of NGC 4755-D during his observing run. This experiment was suggested by N. Z. Scoville. This work was partially supported by the National Science Foundation.

REFERENCES

Abt, H. A., and Biggs, E. S. 1972, *Bibliography of Stellar Radial Velocities* (New York: Latham).
Aitken, D. K., Roche, P. F., Bailey, J. A., Briggs, G. P., Hough, J. H., and Thomas, J. A. 1986, *M.N.R.A.S.*, **218**, 363.
Allen, D. A., and Sanders, R. H. 1986, *Nature*, **319**, 191.
Bailey, J., Hough, J. H., and Axon, D. J. 1984, *M.N.R.A.S.*, **208**, 661.
Becklin, E. E., Matthews, K., Neugebauer, G., and Willner, S. P. 1978, *Ap. J.*, **219**, 121.
Becklin, E. E., and Neugebauer, G. 1968, *Ap. J.*, **151**, 145.
———. 1975, *Ap. J.* (*Letters*), **200**, L71.
Beer, R., Lambert, D. L., and Sneden, C. 1974, *Pub. A.S.P.*, **86**, 806.
Cudaback, D. D., Gaustad, J. D., and Knacke, R. F. 1971, *Ap. J.* (*Letters*), **166**, L49.
Feast, M. W. 1963, *M.N.R.A.S.*, **126**, 11.
Genzel, R., and Townes, C. H. 1987, *Ann. Rev. Astr. Ap.*, **25**, 377.
Goldberg, L. 1985, in *Mass Loss from Red Giants*, ed. M. Morris and B. Zuckerman (Dordrect: Reidel), p. 21.
Herman, J., and Habing, H. J. 1987, in *Late Stages of Stellar Evolution*, ed. S. Kwok and S. R. Pottasch (Dordrecht: Reidel), p. 55.
Humphreys, R. M. 1978, *Ap. J. Suppl.*, **38**, 309.
Jones, T. J. 1987, in *Late Stages of Stellar Evolution*, ed. S. Kwok and S. R. Pottasch (Dordrecht: Reidel), p. 3.
Lacy, J. H., Townes, C. H., Geballe, T. R., and Hollenbach, D. J. 1980, *Ap. J.*, **241**, 132.
Lebofsky, M. J., Rieke, G. H., and Tokunaga, A. T. 1982, *Ap. J.*, **263**, 736.
Mathews, W. G. 1983, *Ap. J.*, **272**, 390.
Rieke, G. H., and Lebofsky, M. J. 1985, *Ap. J.*, **288**, 618.
Rieke, G. H., and Rieke, M. J. 1988, *Ap. J.* (*Letters*), **330**, L33.
Rieke, G. H., Rieke, M. J., and Paul, A. E. 1989, *Ap. J.*, **336**, 752.
Rieke, G. H., Telesco, C. M., and Harper, D. A. 1978, *Ap. J.*, **220**, 556.
Sellgren, K., Hall, D. N., Kleinmann, S. G., and Scoville, N. Z. 1987, *Ap. J.*, **317**, 881.
Serabyn, E. 1984, Ph.D. thesis, University of California, Berkeley.
Wade, R., Geballe, T. R., Krisciunas, K., Gatley, I., and Bird, M. C. 1987, *Ap. J.*, **320**, 570.
Winnberg, A., Baud, B., Matthews, H. E., Habing, H. J., and Olnon, F. M. 1985, *Ap. J.* (*Letters*), **291**, L45.
Yusef-Zadeh, F., Ekers, R., and Morris, M. 1988, poster paper at IAU Symposium 136, The Galactic Center.

G. H. Rieke and M. J. Rieke: Steward Observatory, University of Arizona, Space Science Building, Tucson, AZ 85721