THE ASTROPHYSICAL JOURNAL, 447:L101–L104, 1995 July 10

A CIRCUMSTELLAR H_2O MASER ASSOCIATED WITH THE CIRCUMNUCLEAR MOLECULAR DISK AT THE GALACTIC CENTER?

DEBORAH A. LEVINE,[1,2] DONALD F. FIGER,[1] MARK MORRIS,[1] AND IAN S. MCLEAN[1]
Received 1994 December 19; accepted 1995 April 26

ABSTRACT

In the course of conducting a survey of 22 GHz H_2O masers in the inner Galaxy, we discovered a maser in Sgr A West. It is located ~30″ N and 35″ E of Sgr A*, near the edge of the eastern arm of the radio minispiral, which presumably coincides with the inside edge of the circumnuclear disk. Furthermore, the radial velocity of the maser is remarkably similar to that expected for gas in the circumnuclear disk at this location. The maser coincides with a luminous, reddened star having a bolometric magnitude and IR spectrum characteristic of an M supergiant. Its extinction is consistent with a location in the inner Galaxy, near or within the circumnuclear disk. If this star formed within the circumnuclear disk, it is the first known case of a recently formed star (10^7–10^8 yr ago) in the central 2 pc which can be associated with the gaseous structure in which it was born. Its formation in such a highly sheared and turbulent environment presents a challenge to our understanding of effective star formation mechanisms.

Subject headings: Galaxy: center — infrared: stars — masers — stars: AGB and post-AGB — stars: formation — supergiants

1. INTRODUCTION

Indicators of recent star formation near the Galactic center have been noted for some time. For example, IRS 7, a red supergiant located in the central parsec (Sellgren et al. 1987), the relatively blue objects in the central cluster, IRS 16 (Tamblyn & Rieke 1993), and the presence of hot young He emission-line stars (Krabbe et al. 1991) have often been taken to imply an episode of star formation ~10^7 yr ago. However, given the unusual conditions of the inner Galaxy, star formation is difficult. Morris (1993) argued that tidal forces, magnetic field pressure, and large internal turbulence create conditions which allow cloud collapse only by external influences such as shocks or cloud-cloud collisions, and that such conditions would be likely to lead to an initial mass function (IMF) favoring high-mass stars.

In a 22 GHz VLA[3] survey of *IRAS*-selected H_2O maser candidates projected within ~300 pc of the Galactic center (Levine 1995; Levine & Morris 1994; Taylor, Morris, & Schulman 1993), we have serendipitously discovered an H_2O maser 45″ from Sgr A*. The maser position is coincident with the inner edge of the Galactic circumnuclear disk (CND), and the maser has been identified with a red star observed in a near-infrared Galactic center survey project (Figer 1995).

The CND is a clumpy collection of clouds having a large velocity dispersion, distributed predominantly in a rotating torus centered on Sgr A*. This inclined disk is present at radii from 1.5 to 7 pc (Jackson et al. 1993) and rotates with a circular velocity of ~110 km s^{-1}. There are local deviations from the overall rotation at ~30 km s^{-1} and even larger deviations in the western segment. The CND is generally considered to be an accretion feature. Rieke (1989) notes that its size scale is similar to that inferred for the accretion disks of Seyfert galaxies. There is evidence for inflow through the disk; Jackson et al. (1993) find an inflow of neutral gas of 10^3–10^4 $M_\odot$ in about 10^6 yr into the central cavity. The fate of this gas may be star formation (Krabbe et al. 1991), or it may leave the region as a wind (e.g., Wardle & Königl 1990).

2. OBSERVATIONS

2.1. 22 GHz *VLA Data*

We used the VLA on 1993 October 4, 8, and 9 in the DnC hybrid configuration to survey *IRAS*-defined 22 GHz H_2O maser candidates. At 1.3 cm and low Galactic latitudes, the DnC configuration produced a fairly circular synthesized beam of ~3″.3 diameter. The primary beam is ~1′.5. The uncertainty in the maser position is dominated by the uncertainty in the position of Sgr A* at $17^h\ 42^m\ 29^s.314$, −28°59′18″.3 (1950) ~±0″.2 (Rogers et al. 1994).

Over the course of our 15 hr run, we observed the field centered on Sgr A* 23 times, in order to use the point source as a phase calibrator. Each observation consisted of two consecutive 90 s snapshots at overlapping and staggered frequency settings such that the total spectral coverage for the Sgr A* field was ±172 km s^{-1} with 5 km s^{-1} velocity resolution. The ±98 km s^{-1} velocity range received coverage in all 23 observations.

The data were edited and calibrated in the standard way using AIPS. The Sgr A* data were iteratively self-calibrated using increasingly refined CLEAN map models. CLEAN channel maps of the Sgr A* field were made as a check on the self-calibration quality; it was during inspection of these channel maps that the maser in the field was discovered. The channel map where the maser emission peaks is presented in Figure 1 (Plate L19). The channel maps have an average rms noise of 8 mJy, allowing very significant detection of the 347 mJy maser. Variability of the maser over the 5 day period of the observations is not more than 15%.

[1] Departments of Physics and Astronomy, UCLA, Los Angeles, CA 90024.
[2] Infrared Processing and Analysis Center, MS 100-22, California Institute of Technology, Pasadena, CA 91125.
[3] The Very Large Array (VLA) is operated by Associated Universities Incorporated under cooperative agreement with the National Science Foundation.

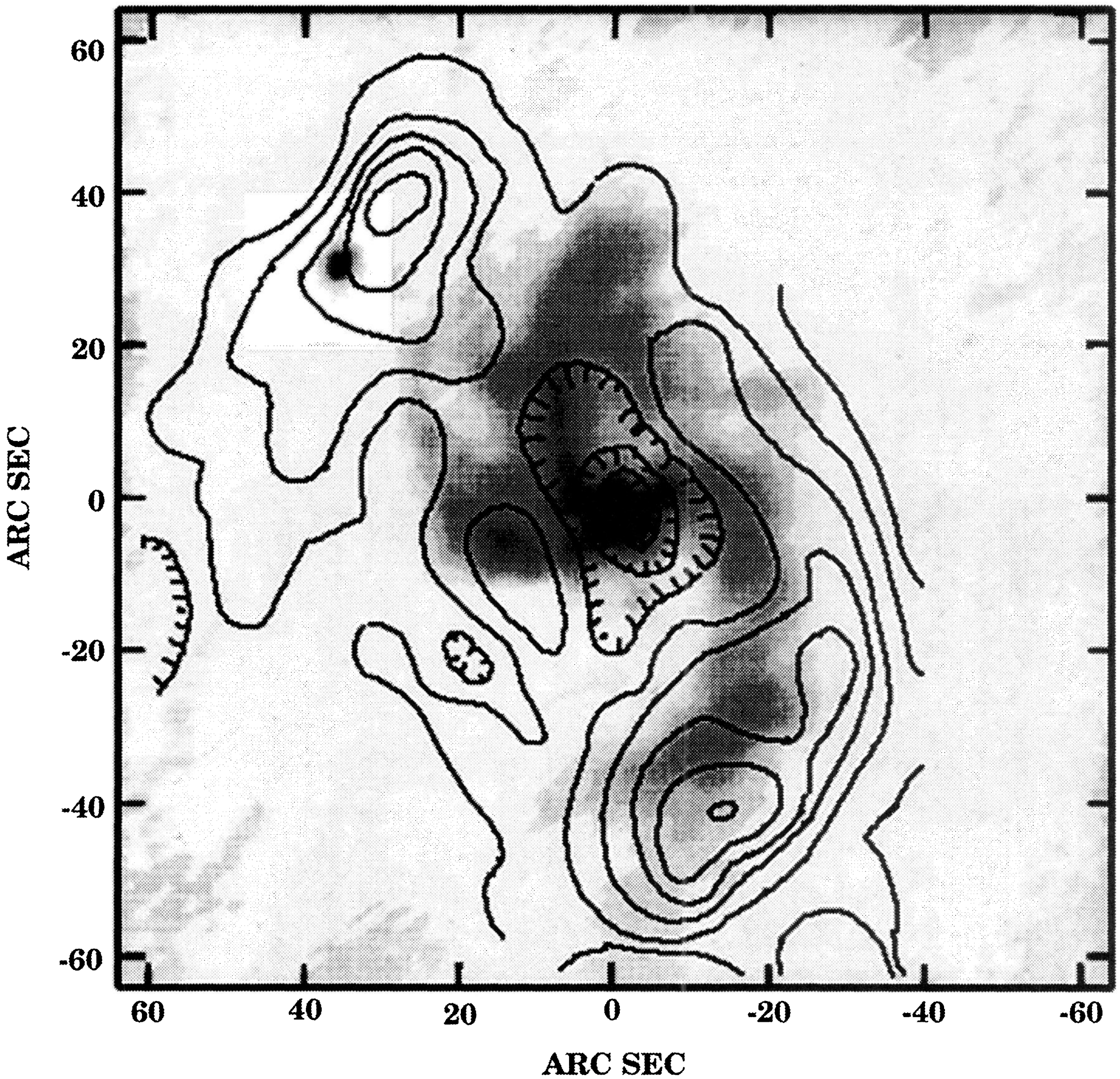

FIG. 1.—Sgr A* field with all data combined. Inset at the correct location is the 45.3 km s^{-1} channel map of the portion of the field containing the maser. Contours are HCN $J = 3 \rightarrow 2$ emission from Jackson et al. (1993).

LEVINE et al. (see 447, L101)

2.2. *Near-IR Observations*

As part of a survey to find hot, young, emission-line stars in the Galactic center, we surveyed $\sim 24' \times 12'$ using the UCLA twin-channel infrared camera (McLean et al. 1993, 1994) on the Lick Observatory 3 m Shane telescope, which gives a plate scale of $\sim 0''.7$ pixel^{-1}. The imaging surveys, done in 1994 June, used broadband H and K' filters as well as narrow-band filters centered at 2.058 μm [$(\lambda/\Delta\lambda) \sim 100$], 2.085 μm (80), 2.165 μm (100), 3.09 μm (80), and 3.15 μm (80); pairs of wavelengths are observed simultaneously.

The imaging surveys were followed by a targeted spectroscopic survey using the same setup in 1994 July. H and K spectra were obtained by inserting grisms into each beam ($R_H \sim 520$ and $R_K \sim 540$). Additional data were obtained in 1994 mid-October using the same equipment with "dust" ($\lambda = 3.28$ μm, $\lambda/\Delta\lambda = 45$) and nbL ($\lambda = 3.6$ μm, $(\lambda/\Delta)\lambda = 45$) filters.

Astrometry for the images was done by offsetting from IRS 7 using the position determined by Becklin et al. (1987), resulting in positions good to $\sim 0''.5$. The position of the infrared counterpart coincides with the maser position to within $0''.5$ and is coincident with extended H_2 and Brγ emission (DePoy, Gatley, & McLean 1989), associated with the eastern arm of the minispiral. The IR counterpart is unresolved.

Haller (1992) observed the star identified as the maser counterpart at H and K, and this star may also be associated with IRS 24 or 23. We note that there is no source in our near-IR images within several arcseconds of the stated position of IRS 23 (Lebofsky et al. 1982a) ($\sim 11''$ south of the maser counterpart) and that, while there is a source near the stated position of IRS 24 ($\sim 5''$ NW of the maser counterpart), it is about 1 magnitude fainter than the maser counterpart. Our images are consistent with Haller's source list, and we speculate that the maser counterpart may have been a source of confusion or contamination in the literature on IRS 23 and 24.

The infrared imaging survey frames were bias-subtracted, sky-subtracted, flat-fielded, and registered, and aperture photometry was performed with DAOPHOT routines in IRAF. IRS 9 and IRS 11 were used to calibrate the zero points at H and K (Becklin et al. 1978), while IRS 7 and IRS 3 were similarly used at nbL (Tollestrup, Capps, & Becklin 1989). It was assumed that the flux density in the nbL filter is the same as that which would be measured in a classical L filter. Measurements at K' were transformed into K-magnitudes using the transformation, $K = K' - 0.2(H - K)$ as per Wainscoat & Cowie (1992). The photometry gives $K = 8.30$, $H - K = 2.47$, $K - L = 1.95$, where errors are due to uncertainties in the zero-point calibrations and are likely to be less than 0.2 mag.

The two-dimensional spectra were reduced by subtracting a sky/bias/dark frame, taken by nodding the telescope along the slit, and using dome flats. A-type main-sequence stars were observed at a similar time and air mass to that of the maser counterpart to correct for atmospheric absorption. Brackett series absorption was removed from these spectra by interpolation. The frames were calibrated in wavelength using the sky OH emission lines, then one-dimensional spectra were extracted with the IRAF APEXTRACT routines, using interactively fitted apertures. The immediate locale of the maser counterpart is contaminated by H_2 and Brγ line emission, so an additional background component had to be subtracted.

The extracted spectra were co-added for the three slit positions, corrected for atmospheric absorption, dereddened based upon the extinction derived from the photometry and the extinction law of Rieke, Rieke, & Paul (1989), scaled according to a blackbody fit to the atmospheric standard star, and then flux-calibrated on an absolute scale by fitting the flux density to that measured during the June run. The spectra are shown in Figure 2.

3. RESULTS AND DISCUSSION

Figure 1 shows the location of the new maser source at 17^h 42^m $32^s.00$, $-28°58'47''.8$ (1950), near the eastern arm of the minispiral, with the HCN ($J = 3 \rightarrow 2$) contours from Jackson et al. (1993) overlain. This position is $47''.3$ (1.9 pc at 8.5 kpc) from the position of Sgr A*. The maser is clearly superposed on the CND and is, in fact, close to the position of the HCN peak. The maser has a double-peaked spectrum (Fig. 3) typical of circumstellar H_2O masers (Palagi et al. 1993), with peaks at 45.3 and 55.8 km s^{-1}, implying a systemic velocity of $\sim 50.5 \pm \sim 5$ km s^{-1}.

Lindqvist, Winnberg, & Forster (1990) conducted a single-dish search for H_2O emission around a sample of 33 OH/IR stars (Winnberg et al. 1985) in the inner 50 pc. They detected 22 GHz maser emission around four of the OH/IR stars, two of which were within $40''$ of our position; while the positions of the OH/IR stars are distinct from our H_2O maser, these pointings would have put the position of our source barely within their half-power beam radius. However, they do not seem to have detected it. Both their H_2O masers have spectra, hence systemic velocities, consistent with the spectra of their OH masers. Thus, it seems very likely that their H_2O sources are, in fact, the targeted OH/IR stars and not the source that we detected. At their epoch of observation, the peaks of their masers were at ~ 0.4 Jy to ~ 1.2 Jy, which our VLA observations could easily have identified. That we did not detect either of these sources we attribute to the notorious variability of H_2O masers (Lewis & Engels 1991). In fact, we did not detect any other 22 GHz masers within $1'.5$ of Sgr A* to a limit of ~ 45 mJy near the center of the mapped field and ~ 1 Jy at the edge of the map.

If the underlying source of the H_2O maser is a spherically symmetric circumstellar shell, then the velocity at the midpoint of the two peaks should be a good tracer of the systemic velocity, though not as reliable as velocities derived from double-peaked OH maser emission from OH/IR stars. We have compared the systemic velocity of our source (50.5 km s^{-1}, the midpoint of the maser spectrum) and its position angle relative to Sgr A* (49° east of north) to a very simple model of the CND—a rotating torus of 1.5–2.3 pc radius with 100 km s^{-1} circular velocity having 70° inclination and major axis at 25° east of north (Jackson et al. 1993). The maser velocity lies on the model velocity curve at its position angle to well within uncertainties in the maser velocity. Thus, both the position and the velocity of the maser source are remarkably consistent with a location in the CND.

The reddening of the IR counterpart also implies that the source may be located in or at the edge of the CND. The star has $H - K$ and $K - L$ consistent with the expected colors of a late-type star given an interstellar extinction equivalent to $A_v \sim 37$, as compared to an average $A_v \sim 30$ for the Galactic

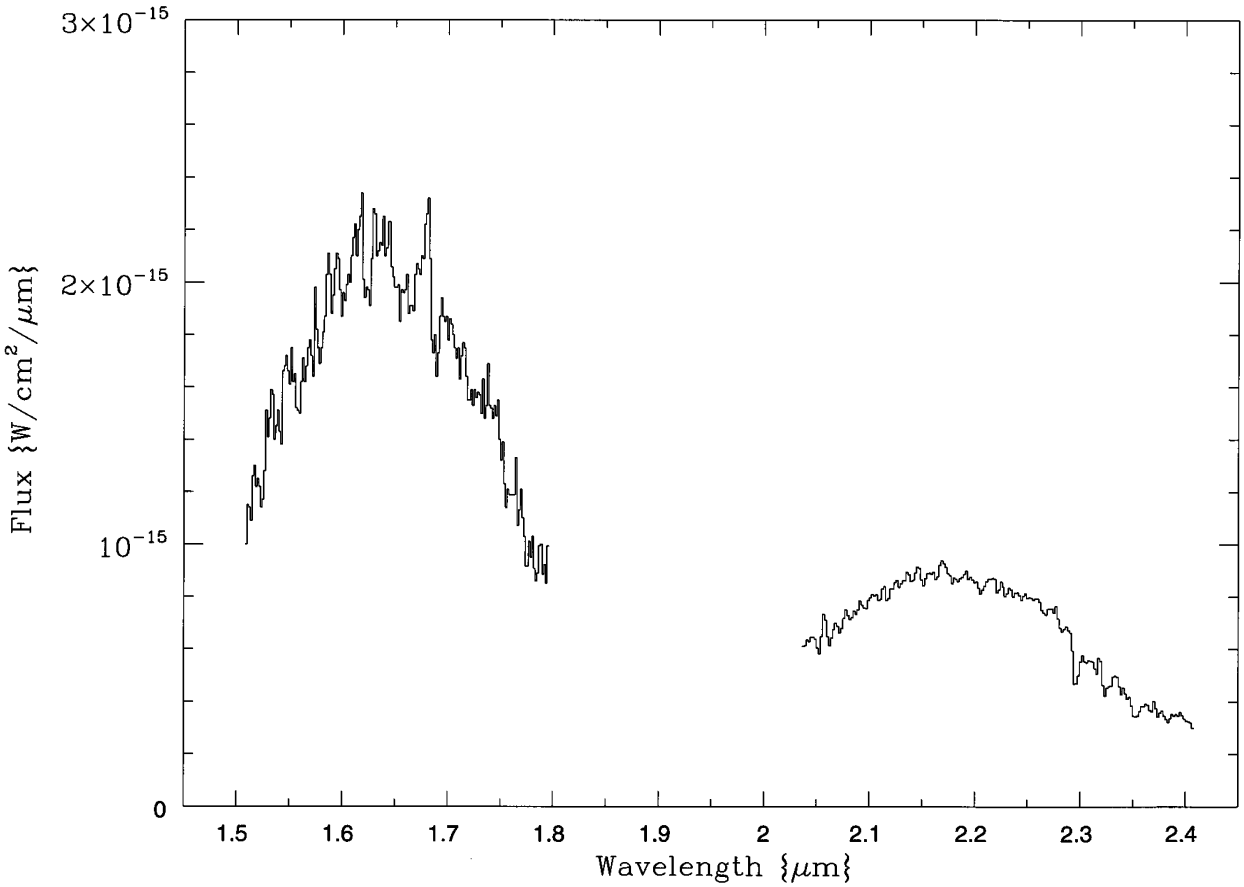

FIG. 2.—Dereddened and flux-calibrated H and K spectra of the IR counterpart. The feature at 2.166 μm is probably a result of diffuse Brγ emission, and features near Brackett series transitions in the H spectrum are contaminated by absorption features in the standard star. Otherwise, flux levels are accurate to within 20%.

center (Becklin et al. 1978; Rieke et al. 1989). This is about the same A_v found for IRS 7 from Lebofsky, Rieke, & Tokunaga (1982b) and Sellgren et al. (1987). We calculated the luminosity of the infrared counterpart using $d = 8500$ pc, $A_H/A_K = 1.56$, and $A_L/A_K = 0.61$ from Rieke et al. (1989) and, for an M5 star, $(H-K)_0 = 0.31$ and $(K-L)_0 = 0.23$ from Koornneef (1983). On a color-color plot, the source lies very near the reddening vector, so the average extinction was used to derive $A_K \sim 4.1$ mag. These values give $M_K = -10.5$ and a luminosity of 1.0×10^5 $L_\odot$ assuming $BC_K = 2.8$ (Elias, Frogel, & Humphreys 1985). This estimate is uncertain as a result of errors in the photometric zero points and in the assumed intrinsic colors. The luminosity is most sensitive to errors in A_K. Assuming an error of 0.1 mag for all bands and intrinsic colors, the error in A_K is 0.3, and the resulting range in luminosity is 8×10^4 to 1.3×10^5 $L_\odot$.

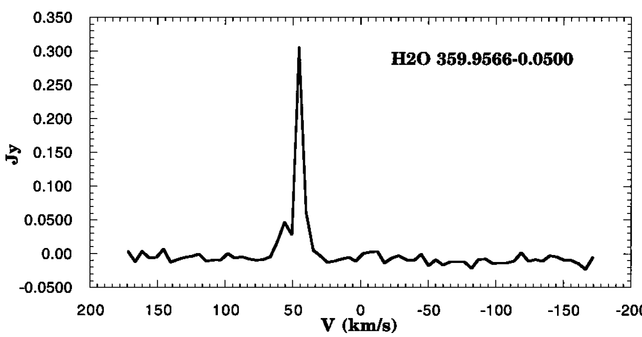

FIG. 3.—The 22 GHz spectrum using the data from all 23 observations.

The IR spectrum shows very deep absorption in the wings of the water absorption bands at 1.9 μm and 2.7 μm and at the CO absorption band heads between 2.3 μm and 2.4 μm. Water and CO absorption both increase with decreasing temperature, but water absorption increases with lower luminosity while CO absorption increases with higher luminosity (Baldwin, Frogel, & Persson 1973). Late-type giants, supergiants, Miras, and carbon stars all show very deep water absorption (Scargle & Strecker 1979), so the IR spectrum is best matched by a very late star. The IR counterpart has characteristics similar to IRS 23, which has $M_K = -10.4$ and a spectrum with very deep water absorption (Sellgren et al. 1987; Lebofsky et al. 1982b). For IRS 23, Lebofsky et al. assign a spectral type of M6 II, while Sellgren et al. conclude it must be later than M7 III.

The high luminosity and cool temperature indicate that this star is an evolved high-mass star with initial mass $\gtrsim 12$ $M_\odot$ and an age of about a few times 10^7 yr (Meynet et al. 1994; Meynet 1994). Therefore, the observed properties are consistent with this source being a young late-type supergiant located just within the inner edge of the CND.

We cannot completely rule out the possibility that this star is on a highly elongated orbit and only coincidentally associated with the CND. However, the constraints imposed by the measured position, velocity, and extinction leave only a small volume of allowable phase space for such orbits, so we regard this as a relatively unlikely scenario. That this star's lifetime is substantially less than the relaxation time for an isotropic cluster of stars at this radius ($\sim 5 \times 10^8$ yr) implies that it would not have had time to drift into its current location from a great distance if it were on an evolving, approximately circular orbit. Therefore, if it is located within the disk, it presumably formed there and would be expected to share the orbit of its parent CND gas. However, it need not have formed in the current manifestation of the CND; tidal, viscous, and magnetic forces, as well as collisions between clumps on a timescale much shorter than the lifetime of such a massive star, may have shredded the parent cloud and channeled the material either in toward the center or out as a wind. The timescale for one complete orbit is $\sim 10^5$ yr, which is the same as the lifetime of clumps in the disk as calculated by Jackson et al. (1993).

If the interpretation of the maser star as a young supergiant embedded in the CND is correct, then, given the factors inhibiting star formation in that environment, one must ask how it could have formed there. Two possibilities are that it formed as a result of a clump-clump collision or as the result of a shock due to an episode of nuclear activity.

4. CONCLUSION

We report on the observation of a late-type supergiant projected within 2 pc of the Galactic center and having circumstellar H_2O maser emission. The position, reddening, and systemic velocity of the source are consistent with a location in the circumnuclear molecular disk. We raise the possibility that the star formed in the CND, in which case it would provide an example of star formation within the last 10^7–10^8 yr in the highly turbulent, magnetized, tidally sheared medium of the Galactic center environment, where star formation mechanisms are not well understood.

This work was partially supported by NSF grants AST9218157 and AST9018527 to UCLA and partially supported by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We would like to thank Michael Jura for a useful conversation.

REFERENCES

Baldwin, J. R., Frogel, J. A., & Persson, S. E. 1973, ApJ, 184, 427
Becklin, E. E., Dinerstein, H., Gatley, I., Werner, M. W., & Jones, B. 1987, in The Galactic Center, ed. D. C. Backer (New York: AIP), 162
Becklin, E. E., Matthews, K., Neugebauer, G., & Willner, S. P. 1978, ApJ, 220, 831
DePoy, D. L., Gatley, I., & McLean, I. S. 1989, in The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 411
Elias, J. H., Frogel, J. A., & Humphreys, R. M. 1985, ApJS, 57, 91
Figer, D. F. 1995, Ph.D. thesis, in preparation
Haller, J. W. 1992, Ph.D. thesis, Univ. Arizona
Jackson, J. M., Geis, N., Genzel, R., Harris, A. J., Madden, S., Poglitsch, A., Stacey, G. J., & Townes, C. H. 1993, ApJ, 402, 173
Koornneef, J. 1983, A&A, 128, 84
Krabbe, A., Genzel, R., Drapatz, S., & Rotaciuc, V. 1991, ApJ, 382, L19
Lebofsky, M. J., Rieke, G. H., Deshpande, M. R., & Kemp, J. C. 1982a, ApJ, 263, 672
Lebofsky, M. J., Rieke, G. H., & Tokunaga, A. T. 1982b, ApJ, 263, 736
Levine, D. A. 1995, Ph.D. thesis, in preparation
Levine, D. A., & Morris, M. 1994, in IAU Symp. 169, Unsolved Problems in the Milky Way, in press
Lewis, B. M., & Engels, D. 1991, MNRAS, 251, 391
Lindqvist, M., Winnberg, A., & Forster, J. R. 1990, A&A, 229, 165
McLean, I. S., et al. 1993, in Infrared Detectors and Instrumentation, ed. A. Fowler (Bellingham: SPIE), 513
McLean, I. S., et al. 1994, in Instrumentation in Astronomy VIII, ed. D. Crawford (Bellingham: SPIE) 457
Meynet, G. 1994, private communication
Meynet, G., Meader, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97
Morris, M. 1993, ApJ, 408, 496
Palagi, F., Cesaroni, R., Comoretto, G., Felli, M., & Natale, V. 1993, A&AS, 101, 153
Rieke, G. H. 1989, in The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 21
Rieke, G. H., Rieke, M. J., & Paul, A. E. 1989, ApJ, 336, 752
Rogers, A. E. E., et al. 1994, ApJ, 434, L59
Scargle, J. D., & Strecker, D. W. 1979, ApJ, 228, 838
Sellgren, K., Hall, D. N. B., Kleinmann, S. G., & Scoville, N. Z. 1987, ApJ, 317, 881
Tamblyn, P., & Rieke, G. H. 1993, ApJ, 414, 573
Taylor, G., Morris, M., & Schulman, E. 1992, AJ, 106, 1978
Tollestrup, E. V., Capps, R. W., & Becklin, E. E. 1989, AJ, 98, 204
Wainscoat, R. J., & Cowie, L. L. 1992, AJ, 103, 332
Wardle, M., & Königl, A. 1990, ApJ, 362, 120
Winnberg, A., Baud, B., Matthews, H. E., Habing, H. J., & Olnon, F. M. 1985, ApJ, 291, L45