The Mid-Infrared Spectrum of the Galactic Center, a Starburst Nucleus

J. P. Simpson[1] and F. C. Witteborn[1]

NASA/Ames Research Center, MS 245-6, Moffett Field, CA 94035-1000

M. Cohen

Radio Astronomy Laboratory, University of California, Berkeley, CA 94720-3411

S. D. Price

Air Force Research Laboratory, VSBC, Hanscom AFB, MA 01731-3010

Abstract. Using the Michelson interferometer on the *Midcourse Space Experiment (MSX)*, we have taken spectra of many positions in the central 25' of the Galactic Center (GC) with a 6' × 9' FOV. The spectral coverage was 380 to 1700 cm^{-1} (6 to 26 μm) and the resolution was ~ 21 cm^{-1}. The spectra exhibit strong UIR/PAH features at 6.2, 7.7, 8.6, and 11.3 μm, in addition to the ionic lines of [Ne II] at 12.8 μm, [S III] 18.7 μm, and [Ar II] 6.98 μm. There are deep silicate absorption features at 10 and 18 μm and a cold continuum increasing at the longest wavelengths. Additional weak features are present in the spectra. We discuss the variation in the extinction at 10 μm as a function of location in the GC. Compared to the MSX spectrum of the Orion Nebula (Simpson et al. 1998), smoothed to the same resolution and multiplied by the estimated GC extinction, the GC spectra have similar PAH features, but the Orion Nebula also has strong lines of [Ne III] 15.6 μm, [S IV] 10.5 μm, and [Ar III] 8.99 μm and its 25 μm continuum is stronger (colder). Thus, the GC exhibits the mid-IR spectrum of a low excitation H II region and a nearby molecular cloud with a surface photodissociation region (PDR). This is in excellent agreement with the canonical model of a starburst nucleus in which the hot stars and molecular clouds are randomly distributed. The outer surfaces of the clouds are photodissociated and ionized by the photons from the stars located outside the clouds. The PAH molecules are transiently heated by the stellar photons. Since the exciting stars are located well outside the clouds, the radiation field is dilute compared to a newly-formed blister H II region like Orion; this dilute radiation field causes the relatively low excitation of the ionic lines.

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[1]SETI Institute

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1. Introduction

Galaxy nuclei are normally classified for their dominant sources of excitation by their optical spectra. Galaxies whose optical spectra exhibit featureless continuum emission (thought to arise from matter falling into black holes) and/or emission from broad lines of a very high range of ionization are known as Active Galactic Nuclei (AGN) or even as QSOs if the normal stellar regions of the galaxy can hardly be detected. Other common sources of excitation of galaxy nuclei are evolved stars or the hot young stars that ionize the interstellar gas and produce optical spectra resembling H II regions.

The different sources of excitation are also distinguishable in the infrared spectra of the galaxies. This is especially useful for those galactic nuclei that are obscured optically by extinction. Infrared spectra have the advantage over the radio spectra in that there are a number of elements that have emission lines from both low and high levels of ionization. Moreover, the dust that is the source of the infrared continuum also has features that can be used in identification of the dust composition and the source of the excitation. Roche et al. (1991) compared the 10 μm spectra of a number of galaxies of known classification from optical spectra. They found that galaxies with H II region nuclei have spectra dominated by the unidentified infrared features (UIR) that are often attributed to PAHs plus emission lines of [Ne II] at 12.8 μm. On the other hand, they found that galaxies regarded as AGNs have either featureless spectra or spectra showing the 10 μm silicate feature in absorption but no PAHs or atomic forbidden lines.

Spoon et al. (1998) and Genzel et al. (1998) used *ISO* to measure mid-IR spectra of a large number of galaxies to try to identify the source of the excitation of the class known as Ultraluminous *IRAS* Galaxies. Genzel et al. discovered that a good criterion is found on a plot of the ratio of the high to low excitation forbidden lines versus the ratio of the 7.7 μm PAH feature to the adjacent continuum. The H II region (also known as starburst) galaxies have low excitation forbidden lines and strong 7.7 μm PAH features whereas the AGNs have much higher excitation forbidden lines and essentially no 7.7 μm PAH feature. Some of the Ultraluminous *IRAS* Galaxies have ratios more like the starburst galaxies and some have ratios more like the AGNs; thus Genzel et al. concluded that these ratios can be used for galaxy classification from infrared spectra.

Some examples are M82 and the Circinus Galaxy. M82 (Lutz et al. 1998a) is a good example of Roche et al.'s H II region galaxy; it is also called a starburst galaxy because of the dominance of the spectrum by hot young stars and their effects on the surrounding molecular clouds. On the other hand, Circinus Galaxy (Moorwood et al. 1996) has some features of the H II region spectrum — PAHs and the low excitation molecular and ionic lines — but it also has high excitation lines like [Ne V], [O IV], and [Ne VI], which require photons that are much more energetic than found in any H II region and which consequently indicate a high energy central source. The weaker PAH feature could be due to additional continuum from dust heated by the central AGN or the PAH molecules could be dissociated by the high energy photons (e.g., Lutz et al. 1998b).

Lutz et al. (1996) published a spectrum of the Galactic Center taken in a 14″ by 20″ aperture with SWS on *ISO*. The spectrum is dominated by the deep 10

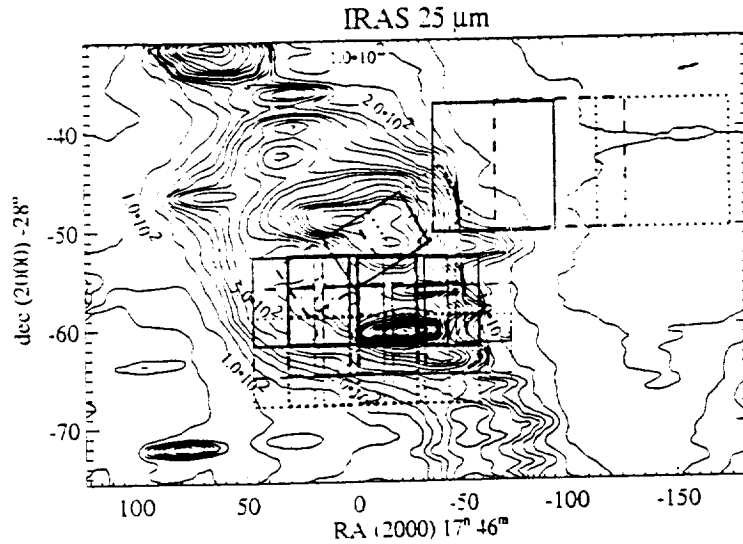2

Figure 1. The positions measured in the Galactic Center are plotted on a 25 μm contour map from *IRAS*.

and 20 μm silicate absorption features: also present are hydrogen recombination lines and the forbidden lines typically found in H II regions. Although there is a very small amount of [O IV] in the spectrum, for the most part the excitation is low. Lutz et al. attributed the [O IV] to hot old stars like Wolf-Rayet stars (known to exist in the Galactic Center) rather than to hard photons from an AGN. Genzel et al. (1998) put the Galactic Center into the starburst group. On the other hand, there is no evidence for PAHs in the *ISO* spectrum of Lutz et al. (1996); Genzel et al. suggested that the PAH molecules are destroyed or transformed in the radiation field of the region around Sgr A*.

The Galactic Center clearly contains indications of both AGN-like excitation sources (Sgr A* and the lack of PAH features in the $14'' \times 18''$ region surrounding it) and young hot stars (the central cluster, AFGL 2004/Quintuplet cluster, and the Arches Cluster and their H II regions). In order to compare the Galactic Center with the nuclei of external galaxies, one really should measure the GC spectrum as integrated over comparable physical sizes. This means either integrating over a number of different locations or measuring the spectrum in a much larger field of view. This paper presents mid-IR spectra of the Galactic Center taken in September and October, 1996, with the *Midcourse Space Experiment (MSX)* Michelson interferometer.

2. Observations

The *MSX* Michelson interferometer had 6 Si:As impurity-band conduction detectors with fields of view of 6' by 9' and 11' by 11'. (The *MSX* instruments are further described by Mill et al. 1994 and Egan et al. 1998.) We used the 6' × 9' detector with the widest wavelength coverage to map the Galactic Center in a 7 by 3 position grid (RA by Dec). At the same time, spectra from 6 to 9 μm were measured in an 11' × 11' detector; however, because of the lower signal, these spectra were averaged, resulting in only 3 positions plotted. On a different orbit, the telescope scanned repeatedly back and forth over the Galactic Center. Here, the spectra from the 6' × 9' detector were averaged for 3 positions in Galactic longitude, with the center position being the base of the Arched Filaments. For all spectra, the resolution was ~ 21 cm^{-1}. Figure 1 shows these positions overlaid on the *IRAS* 25 μm contours[1] and Figures 2 – 4 show the spectra obtained at these positions.

The features immediately apparent in all these spectra are the 10 and 18 μm silicate absorption features, the strong PAH features at 6.2, 7.7, and 11.3 μm (the 8.6 μm is partly submerged by the 10 μm absorption), and the low excitation lines of [Ar II] 6.98 μm and [Ne II] 12.8 μm. The 18.7 μm [S III] line is also visible as is the 17.0 μm line of H_2 (S1) at some positions. What are *not* apparent are any strong high excitation forbidden lines, although a weak [Ne III] 15.6 μm line could be present. These spectra are very similar (albeit with lower resolution and more extinction) to those of M82, the prototypical starburst galaxy.

Would we see the high excitation lines at this low resolution? The *MSX* interferometer also measured the spectrum of the Orion Nebula with 2 cm^{-1} resolution (Simpson et al. 1998). The higher excitation lines of [Ar III] 8.99 μm, [S IV] 10.5 μm, and [Ne III] 15.6 μm are clearly present and strong; in addition, the PAH features from the Orion photodissociation region (PDR) plus molecular hydrogen lines from the Orion molecular cloud are present.

Figure 5 shows the Orion Nebula spectrum smoothed to the same resolution as the Galactic Center spectra and multiplied by $\exp(-\tau_{9.7} * \kappa_\nu)$ where $\tau_{9.7} = 3.2$, 3.6, and 4.0. The extinction coefficients, κ_ν, as a function of frequency, ν, were estimated from the *ISO* Galactic Center spectrum of Lutz et al. (1996) (fit by the sum of 3000 K and 250 K blackbodies multiplied by the derived extinction coefficients times $\tau_{9.7} = 3.6$) and footnote 7 of Genzel et al. (1998) and normalized to unity at 9.7 μm. The chief differences with the Galactic Center spectra are that the Orion Nebula has a much stronger cold continuum and that the higher excitation lines are easily visible at the lower resolution. Even the [Ar III] and [S IV] lines are visible, the [Ar II] line is much weaker, and the ratio of [Ne III]/[Ne II] is much larger in Orion than in the Galactic Center (the two neon lines have very similar extinctions).

Thus we can conclusively say that the Galactic Center in a large field of view exhibits strong PAH features and low ionization; its mid-IR spectrum can best be described as that of a starburst galaxy.

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[1]The IRAS image was obtained using the facilities of the IPAC, which is funded by NASA as part of the IRAS extended mission program under contract to JPL.
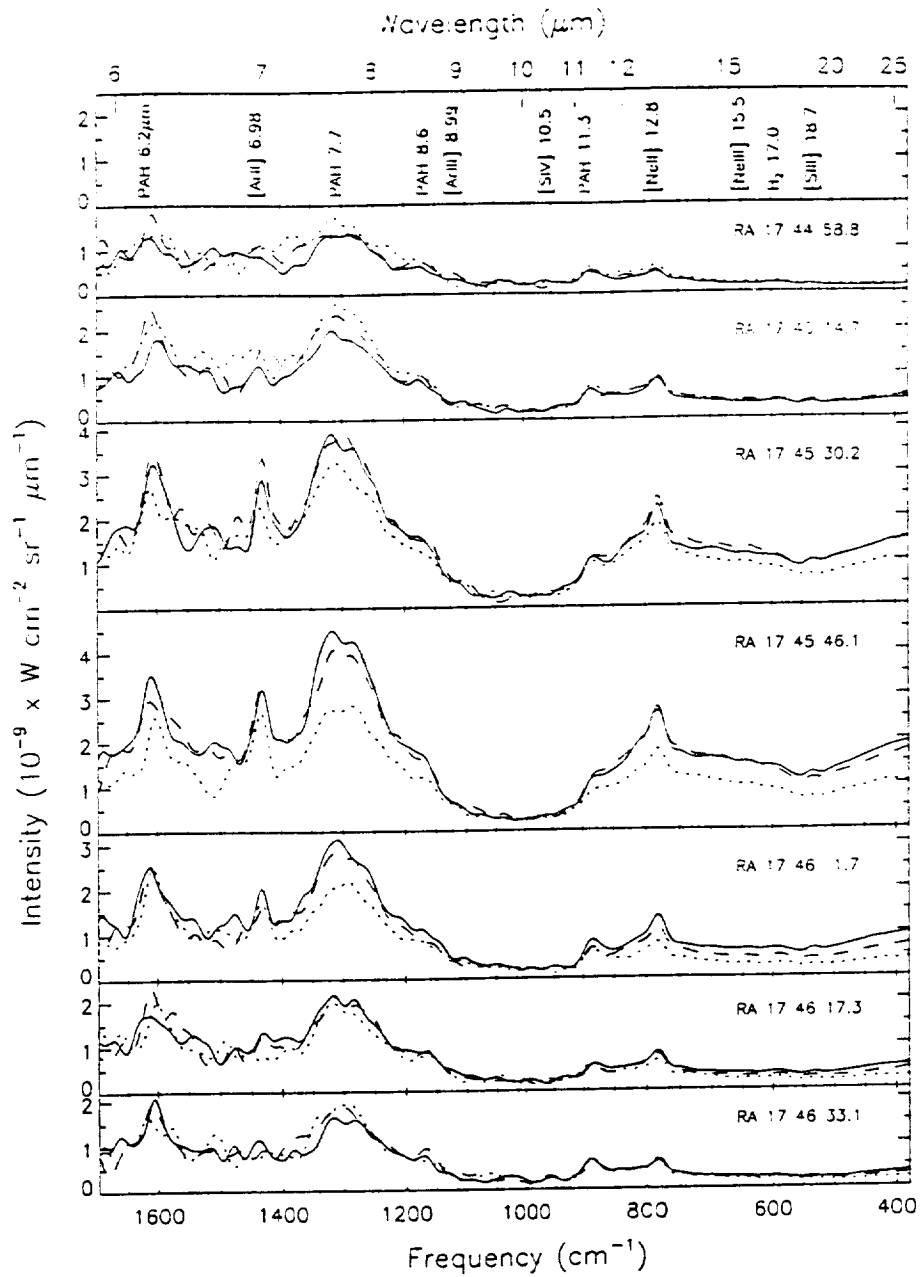
Figure 2.   The 21 spectra of the Galactic Center are plotted. The 7 right ascensions (J2000) are plotted separately; the 3 declinations are plotted as north (solid), center (dashed), and south (dotted).
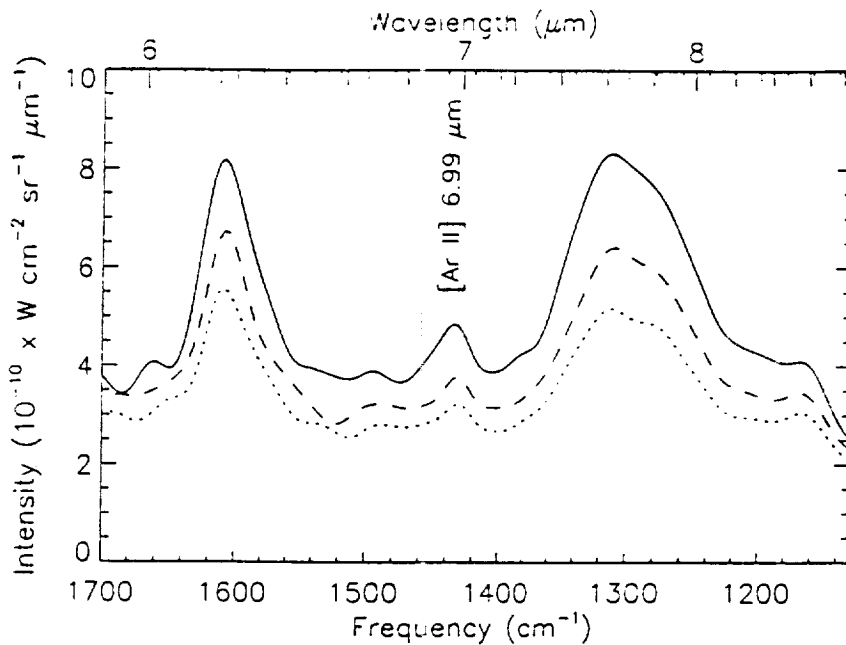
Figure 3.   Spectra from the 11' × 11' detector are plotted. The 3 right ascensions are plotted as east (solid), center (dashed), and west (dotted).
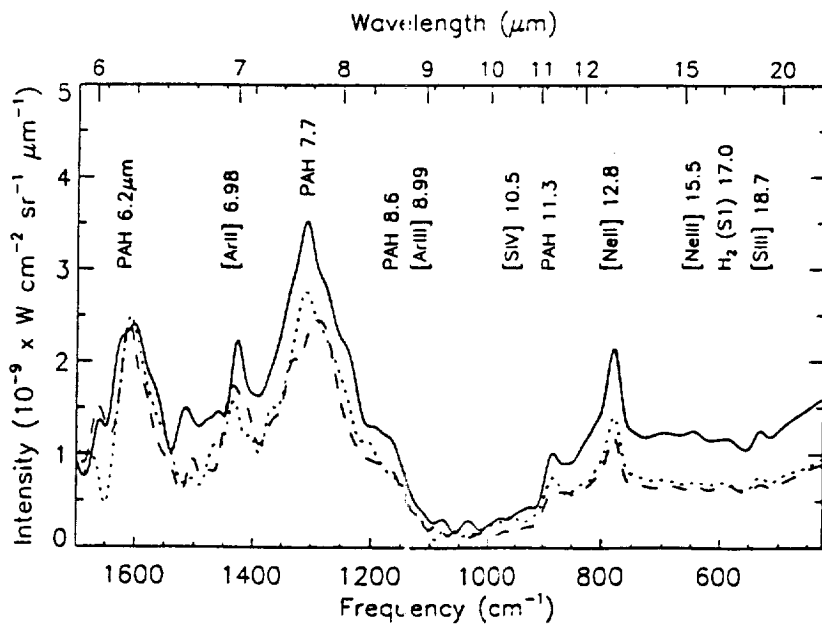

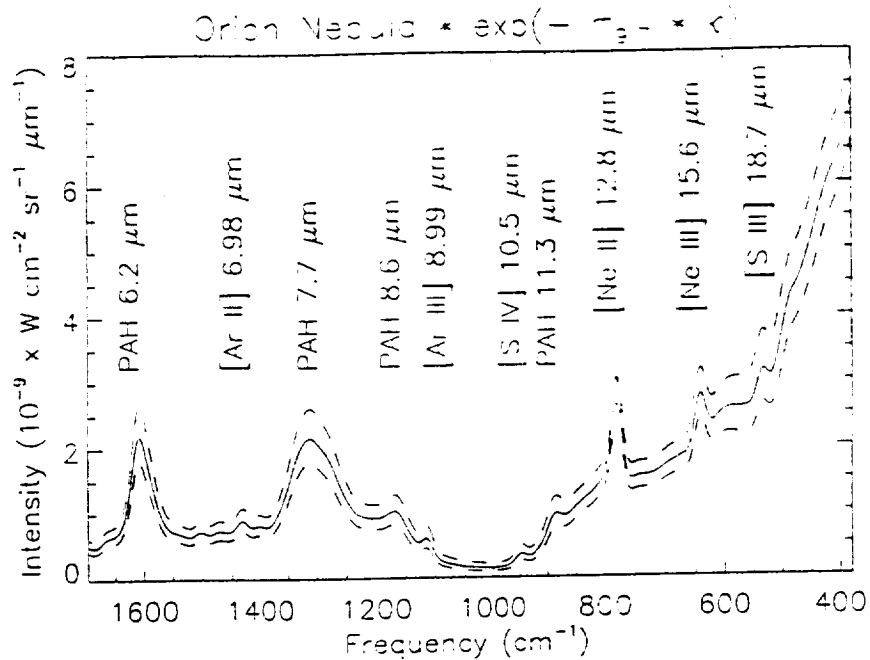Figure 4.   Three spectra of the Arched Filaments region are plotted.

Figure 5.   The spectrum of the Orion Nebula. smoothed to the same resolution as the Galactic Center spectra and multiplied by extinctions corresponding to $\tau_{9.7} = 3.2$, 3.6, and 4.0.

3.   Discussion

It appears from Figure 2 that the extinction is not the same for all the spectra. For example, the 8.6 and 11.3 μm PAH features are much more distinct in the spectra of the outer positions than in the spectra for the center. We have attempted to find the values of $\tau_{9.7}$ such that when each spectrum is multiplied by exp(+ $\tau_{9.7} * \kappa$), the resulting spectrum is flat through the 10 μm silicate feature. (The estimated contribution of the zodiacal emission (Leinert et al. 1998) for solar elongation $\sim$ 73 deg and ecliptic latitude $\sim$ 6 deg was removed first.)   Figure 6 shows the variation in the extinction as determined by this method.   For future work we will use these spectra to estimate the relative contributions from the different components. For example, the ratio of PAHs to 25 μm continuum is smaller closer to Sgr A than it is further out.

Wolfire, Tielens, and Hollenbach (1990) discussed the application of PDR theory to H II regions and galactic nuclei. Their Figure 7 showed 3 different possible scenarios: a) hot stars closely associated with their natal molecular clouds such that the far-UV radiation field on the clouds is high, as occurs in an H II region and its PDR, b) hot stars and molecular clouds randomly distributed such that the radiation field is the average interstellar field, and c) molecular clouds heated by an AGN. Scenario b may be the most applicable to the Galactic Center. The low ionization would be due to the stars being located, on the average, at some distance from the molecular clouds. We must note, on the other hand, that all the H II regions in the inner Galaxy are of low
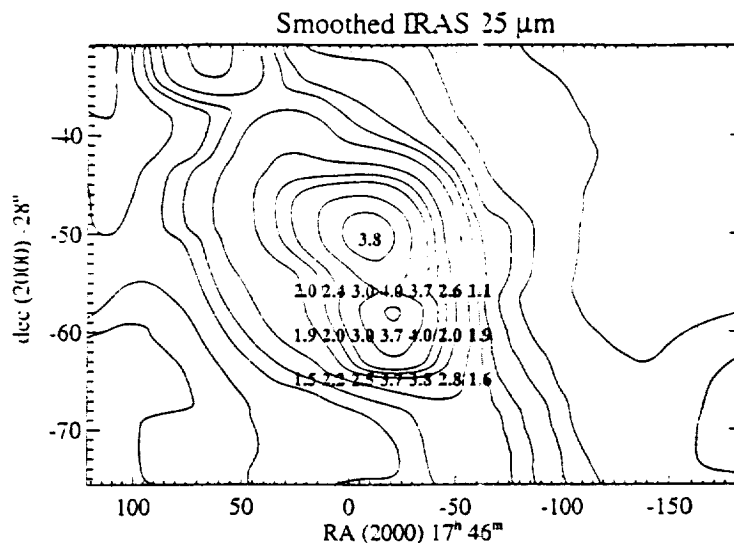
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Figure 6. The estimated optical depth, $\tau_{9.7}$, is plotted on the *IRAS* 25 μm contour map smoothed to a resolution of 6', approximately corresponding to FOV in the *MSX* interferometer.

excitation; the other effect that could be important here is that high abundance H II regions are of low excitation because of their high UV opacity (Simpson et al. 1995).

Scenario b is compatible with the FIR observations of the H II regions in the Galactic Center - low gas density low ionization, strong PDR lines and continuum indicating excitation by the known clusters plus other random stars (Erickson et al. 1991; Colgan et al. 1995; Colgan et al. 1996; Simpson et al. 1997; Timmermann et al. 1997).

4. Conclusion

When observed in a large FOV, the Galactic Center shows strong PAH features, low excitation lines (H_2, [Ar II], [Ne II] [S III]), essentially no higher excitation lines ([Ne III]/[Ne II] $<<$ 1) even compared to the Orion Nebula, and deep silicate absorption at 10 and 18 μm, especially right on the Galactic plane. These are the same characteristics that are seen in starburst galaxies and that are not apparent in AGNs, which have high excitation lines, flatter continua, and/or weak PAH features. In fact, the Galactic Center appears to be of even lower excitation than some starburst galaxies, such as M 82. The very low excitation in the Galactic Center could be due to either high abundances in

the exciting stars and H II regions or to the ionizing radiation field being more diffuse than is found in the young H II regions surrounding newly formed stars. This diffuse radiation field could be the result of a starburst occurring within the last few million years but long enough ago that the hot stars are no longer physically associated with the molecular clouds of their birth.

References

Colgan, S. W. J., Erickson, E. F., Simpson, J. P., Haas, M. R., & Morris, M. 1996, ApJ, 470, 882

Colgan, S. W. J., Simpson, J. P., Erickson, E. F., Haas, M. R., Rubin, R. H., & Morris, M. 1995, BAAS, 27, 884

Egan, M. P., Shipman, R. F., Price, S. D., Carey, S. J., Clark, F. O., & Cohen, M. 1998, ApJ, 494, L199

Erickson, E. F., Colgan, S. W. J., Simpson, J. P., Rubin, R. H., Morris, M., & Haas, M. R. 1991, ApJ, 370, L69

Genzel, R. et al. 1998, ApJ, 498, 579

Leinert, C. et al. 1998, A&AS, 127, 1

Lutz, D. et al. 1996, A&A, 315, L269

Lutz, D. et al. 1998a, in Star Formation with the *Infrared Space Observatory*, ASP Conf. Ser. 132, ed. J. L. Yun & R. Liseau (San Francisco: ASP), 89

Lutz, D., Spoon, H. W. W., Rigopoulou, D., Moorwood, A. F. M., & Genzel, R. 1998b, ApJ, 505, L103

Mill, J. D. et al. 1994, J. Spacecraft & Rockets, 31, 900

Moorwood, A. F. M. et al. 1996, A&A, 315, L109

Roche, P. F., Aitken, D. K., Smith, C. H., & Ward, M. J. 1991, MNRAS, 248, 606

Simpson, J. P., Colgan, S. W. J., Cotera, A. S., Erickson, E. F., Haas, M. R., Morris, M., & Rubin, R. H. 1997, ApJ, 487, 689

Simpson, J. P., Colgan, S. W. J., Rubin, R. H., Erickson, E. F., & Haas, M. R. 1995, ApJ, 444, 721

Simpson, J. P., Witteborn, F. C., Price, S. D., & Cohen, M. 1998, ApJ, 508, in press

Spoon, H. W. W., Genzel, R. & Lutz, D. 1998, in Star Formation with the *Infrared Space Observatory*, ASP Conf. Ser. 132, ed. J. L. Yun & R. Liseau (San Francisco: ASP), 414

Timmermann, R. et al. 1996, ApJ, 466, 242

Wolfire, M. F., Tielens, A. G. G. M., & Hollenbach, D. 1990, ApJ, 358, 116

SUMMARY OF 1998 PROGRESS ON IOTA TECHNOLOGY
by Fred Witteborn

Our work on IOTA (Interferometric Optical Telescope Array) technology improvement has been directed towards analysis of the performance of the tip-tilt mirror system. (This system senses motion of the star image on a camera caused by atmospheric disturbances or other causes and then corrects for them by moving a mirror in the optical path.) We designed a light source that could be injected into the optical path of either of the IOTA telescopes and made to appear as a point source at infinite distance. In addition a piezo electric actuator was used to vibrated the light source to simulate the atmospheric effects on a stellar image. This provided a quantitative input to the IOTA control system that could be varied over important parameters such as frequency, amplitude and brightness. These parameters as well as IOTA parameters (e.g. feedback and camera scan rate) were varied while we recorded the image centroid in order to provide a systematic study of the performance of the guidance system. Three trips to IOTA provided an opportunity to adapt the artificial source to the telescope geometry, perform the desired tests and to make angular diameter measurements of several stars (the primary function of IOTA).

The tests showed that the tip-tilt control system corrects well for image motions only at frequencies of 3 Hz or lower, whereas atmospheric motion occurred in the 30 - 50 Hz frequency range during our observations. The impact of this deficiency in the tip-tilt control system is wavelength dependent, since the main degradation in performance depends on the phase difference between wavefronts from the two telescopes. At the longest wavelengths at which IOTA is used (K-band or 2 microns), the degradation in performance is only 10%, but at J-band (1.2 microns) this increases to 25%, and at visible (0.5 microns) the degradation is quite large. A faster tip-tilt system is needed for work at the shorter wavelengths. Future work may be directed at a faster readout of the image position which could enable the tip-tilt control to speed up.

Some of the real-time data from angular diameter measurements were given to Robert Mah and his group in Code IC (Computational Sciences Division) to test their neural network programs for correcting for phase differences between the two telescopes. We hope to test their "fringe packet tracking" program in actual observations if the IOTA work goes into a second year. (These must first be adapted to the IOTA computers.)

The data mentioned above were incorporated in a detailed report on the tip-tilt system entitled "IOTA Tip-tilt Performance Analysis" and sent to Wes Traub (Harvard/SAO) in July '98.

The Wide-field Infrared Explorer (WIRE) mission is scheduled for launch approximately March 1, 1999. Although designed mostly for a 12 and 25 micron survey of galaxy evolution at high red-shift, time will be allotted for study of stars included serendipitously in the main survey's coverage of the galactic polar regions plus a few targets proposed by AIs ("Additional Investigators") near the galactic plane. AIs Dana Backman and John Stauffer will be collaborating with WIRE science team member Mike Werner to search with WIRE for stars with mid-IR excesses as possible examples of planetary construction debris at terrestrial temperatures.

Between May and August of 1998 work was done to investigate the possible limits of WIRE's ability to detect circumstellar dust by simulating a similar program in less sensitive IRAS data. This included: A) using 12 and 25 micron data archived in the IRAS Faint Source Catalog (FSC) to find the number of stars with mid-IR excesses in a given population, then B) estimating WIRE's sensitivity to similar excesses around fainter stars at the same wavelengths.

Much of this work included writing a program in Perl to parse through star catalog lists and select stars in a region around a given RA and Dec. This program can be used during and after the WIRE mission to identify stars in various catalogs which fall in the extragalactic survey fields.

The initial stages of the project included retrieval of a number of star catalogs from the Internet, including the Gliese, HD, Tycho and Hipparcos catalogs, and pertinent data from online versions of the FSC, Michigan spectral catalog, and others.

The RA and DEC values from the HD catalog were unfortunately not of high enough precision to cross reference to the FSC and other necessary catalogs, therefore star coordinates were taken from the Tycho catalog and the list limited to those stars with spectral type determinations in the HD catalog. This list was then reduced to only those stars within a 11.5 degree radius of the North Galactic Pole (NGP) (or 1% of the sky--roughly the area expected to be covered in that vicinity by the main WIRE survey) using the forementioned Perl program.

12 and 25 micron data was obtained by cross-referencing against the FSC. From this, color-color V-[12] vs. B-V and V-[25] vs. B-V plots were made using only stars with IRAS detections (Fqual = 2 or 3). This procedure was repeated for the South Galactic Pole (SGP). Finally, both NGP and SGP data were merged into a single set and the calculations repeated.

Results were that of 598 stars with 12 micron detections, 71 stars or 12% of the population showed excesses at 12 microns, judged by departure of more than 3 times the population scatter from the main sequence line on the color-color plots. From 239 stars with 25 micron detections, 29 or 12% of the population showed excesses at 25 microns. The final count of 25 micron excess stars was best found from a calculation of [12]-[25] excess, due to large uncertainty in the V-[25] vs. B-V plot. Many of the stars found in this work to have excesses are "new" and can potentially be published as an extension of a similar survey performed by Mannings and Barlow (Ap.J. 1998).

Dana Backman's "exozodi.f" FORTRAN program was then used to predict WIRE sensitivity to quantities of dust around different star types at those wavelengths. Slopes calculated from the NGP-SGP data were used to find the average level of photospheric 12 and 25 micron flux for different spectral types. The program then gave a predicted level of flux at those wavelengths emitted by hypothetical dust disks around stars of various spectral types. We obtained lower limits of dust needed to provide an IRAS FSC detection:

At 12 microns: At 25 microns:

A5V > 7000 zodis   A5V > 3800 zodis
F5V > 8000 zodis   F5V > 3200 zodis
G2V > 8000 zodis   G2V > 2250 zodis
K5V > 11000 zodis   K5V > 2000 zodis

The unit "zodi" refers to a dust cloud like the one in our solar system,
extending from 3 AU in to 0.1 AU with approximately constant surface
density of 1 x 10^-7 (geometric optical depth, m^2 per m^2).

These limits are surprisingly high given that the raw sensitivity of the
IRAS FSC should have allowed detection of excesses down to less than 1000
zodis. Among possible explanations are that the population scatter we
found about the main sequence lines on the color-color plots is real and
not instrumental, i.e.: A) Stellar photospheric mid-IR colors have a
substantial scatter at a given B-V, larger than can be explained by
plausible ISM reddening for the fairly bright stars surveyed, and/or B)
many normal main sequence stars have dust excesses with optical depths in
the range of a few thousand zodis.

This in turn indicates that best use of greater WIRE sensitivity to detect
warm circumstellar dust may require substantial ancillary tasks of
collecting ground-based near-IR photometry of photospheres of stars
observed by WIRE and then extrapolating SEDs to the mid-IR using
stellar atmosphere models, star-by-star.