Final Technical Report:

"KWIC: A Widefield Mid-Infrared Array Camera/Spectrometer for the KAO"

PI: Gordon J. Stacey
Cornell University
NASA/AMES Contract: NAG2-1072

This grant covered a one year data analysis period for the data we obtained with the **K**uiper **W**idefield **I**nfrared **C**amera (**KWIC**) on the KAO during CY94 and CY95. A fairly complete list of scientific papers produced, or soon to be produced under this award is contained at the end of this report. Below we summarize some of the highlights of the work we did under this grant.

KWIC Imaging of the Orion Nebula. KWIC was successfully developed under the KAO grants program (NASA grant NAG2-800). First funding arrived in November of 1992, and we flew our first two flights in February of 1994 – just 15 months later. These flights were very successful. We imaged the Orion Nebula in the 37.7 μm continuum and [SiII] 35 μm line and imaged M82 and Arp299 in the 37.7 μm continuum. Our Orion image demonstrates that the 37.7 μm continuum arises in the warm dust associated with the photodissociated surfaces (photodissociation regions, or PDRs) of molecular clouds. We use the brightness and color temperature distribution to ascertain the morphology of the Orion PDR.

The [SiII] image of Orion encompassed the entire Orion A HII region and its enveloping PDR. Most of the emission in the PDR regions of the map appears to coincide very well with our 37.7 μm continuum map indicating a PDR origin for the [SiII] in agreement with theoretical predictions. The [SiII] line emission is very clumpy in the PDR directly imaging the clump spectrum indirectly ascertained by examining the distribution and flux ratios of [CII] and [OI] far-IR fine structure line, and high J CO emission. We also detected very strong [SiII] line emission from the embedded BN-KL star formation region tracing the morphology and physical conditions of the high velocity shock from these very young stars.

KWIC Imaging of Starburst Galaxies. The images of M82 and NGC Arp299 trace the luminosity of embedded star formation regions in these starburst galaxies, thereby providing an extinction free probe of star formation activity. The far-IR continuum distribution in M82 lies within the molecular ring as traced by its bright CO line emission, indicating that the starburst has fragmented the local ISM into small, mostly photodissociated cloudlets. Close inspection of the minor axis profile indicates a weak (2% of the peak) "plateau" of 37.7 μm flux both north and south of the galactic plane. Therefore, there is substantial warm dust at large (~ 300 pc) scale heights, presumably heated by the UV flux that escapes the nuclear starburst along the minor axis. Arp 299 is an extremely IR luminous ($L \sim 8 \times 10^{11}\ L_{\odot}$) interacting galaxy pair. Our high spatial resolution image resolves the system into its two primary sources: "A", the nucleus of IC 694, and "B", the nucleus of NGC 3690. Source "C", the overlap region, is not apparent as a separate source. Our images permit for the first time estimates of the individual source

luminosities: ~ 3.7×10^{11} $L_\odot$, 1.8×10^{11} $L_\odot$, and 0.65×10^{11} $L_\odot$, respectively for sources "A", "B", and "C". The luminosity of the IC 694 nucleus alone is *ten times the luminosity of M82!*

KWIC Imaging of the Galactic Center. We were awarded three flights with KWIC for FY95, the last year of the KAO operation. These flights were taken out of Christchurch, New Zealand, and were also very successful. Our primary goal was to image the Galactic Center in the 31.5 and 37.7 μm continuum. We were able to image the entire circumnuclear ring (CNR), thermal and non-thermal arches, and sickle/pistol region in the 37.7 μm continuum, and all but the non-thermal arches, and sickle/pistol region in the 31.5 μm continuum. The raw images have a spatial resolution of ~ 8.5" and cover a region roughly 15' (RA) by 25' (Dec.) in extent. This large data set is split into two parts for publication. The first paper, on the CNR is to appear in ApJ in February, 99. This paper covers the innermost 2.8' × 3.6' (6.9 × 9.1 pc) regions roughly centered on Sgr A* where the high signal to noise permits image restoration to ~ 3.6" to 5.7" spatial resolution at 31.5 and 37.7 μm, respectively. These images clearly delineate the warm dust in the "mini-spiral", but also show an elliptical structure centered on Sgr A* and intersecting the mini-spiral at the western arc that we identify as the photodissociated inner rim of the circumnuclear disk (CND) or ring. This is the first image of the complete disk, and the first image of both the mini-spiral and CND in a single tracer, thereby permitting detailed studies of the intimate association between these two structures. The 31.5/37.7 μm color temperature map indicates that most of the far-UV flux required to heat the dust grains must come from centrally located sources. The cluster of HeI emission line stars recently identified near Sgr A* is sufficient to provide half the heating for the far-IR ring and mini-spiral structures, the balance is likely provided by O and B stars associated with the cluster. We also find ~ 16 color temperature peaks distributed within the CND that we suggest are the locations of early type (B4 to O9) main sequence stars. To match the observed far-IR fluxes from the ring, we require an unusually high 30 to 40 μm dust grain emissivity and/or an usually high UV albedo.

The far-IR morphology is reproduced by a simple model: an inclined (i ~ 65°), slightly elliptical (e ~ 0.06) torus with one focus at Sgr A*, and two streamers on parabolic orbits with foci at Sgr A*. The torus has an inner radius of 1.58 pc, is ~ 0.4 pc thick, and consists of clumpy cloudlets with characteristic sizes < 0.15 pc. The northern streamer is identified with the northern arm, and the east-west (EW) streamer is identified with the bar and eastern arm structures seen in both their [NeII] fine-structure line emission and the radio continuum. The northern arm is traced in the far-IR continuum from regions ~ 1.4 pc outside of the far-IR ring, to its apparent intersection with the EW streamer. The eastern CND is not detected in the radio continuum due to extinction by the intervening northern arm, which therefore must be nearly in the plane of the CND. Extensions of the EW streamer outside of the CND are apparent to the east, and especially to the northwest. The EW streamer lies ~ 85° out of the plane of the CND and is on a parobolic orbit focused on Sgr A* at a distance of 0.33 pc, with its apex well in front of, or behind Sgr A*.

Our second paper addresses the source of ionization for the thermal arches. The paper is based on the large scale KAO image, but also includes [NeII] (12.81 μm), [SIV] (10.52 μm), and 11.3 μm UIR spectra spectra taken with SpectroCam-10 on the Hale 200" telescope. Our data strongly supports internal ionization for most of the thermal arches. The overlap of [NeII], radio continuum, and far-infrared continuum emission from the arches, the progression of widths ([NeII] is narrowest, far-infrared is widest), and temperature peaks on the arches are naturally

explained by internal heating. If the stars are embedded, the generally uniform luminosity and temperature of the arches places an upper limit of O9 or B0 for the luminosity of the stars. This is consistent with the upper limit determined from the non-detection of [SIV] and the observed [NeII] line flux. The far-infrared luminosity and radio continuum emission integrated over the thermal arches are consistent with an embedded star cluster with its main sequence headed by ~ 57 O9 stars. The morphological and age problems generally associated with internal ionization of the arches may be solved if the arches are taken to be tidally stretched clouds which are older than a few million years.

The observed [NeII] line velocities are constant for the majority of the arches and consistent with prior results. However, the E2 arch has a forbidden velocity of +36 km s^{-1}, and there is a sharp18 km s^{-1} velocity shift across the southern E2 arch. The velocity shift may be due either to two components along the line of sight or shocks propagating through previously photoionized material. . Finally, the far-IR continuum from the Pistol is shifted ~ 10" south of the radio continuum emission indicating that the Quintuplet HeI stars and their associated main sequence OB stars are the ionization source for the Pistol. This paper was just recently submitted to the Astrophysical Journal.

KWIC Imaging of 30 Doradus. We also obtained two color images of the 30 Doradus region of the Large Magellanic Cloud (LMC) and deep images of the η Carinae nebula. This region is of particular interest, as it occurs in a low metallicity dwarf galaxy, yet is the most luminous star formation region in the local group. Apparent in both the 31.5 and 37.7 μm maps is the banana shaped structure representing the photodissociated surface of the parent molecular cloud to the NW. This interface is presented to us roughly edge-on. The KWIC FIR continuum images peak between the HII region, as traced by its near IR hydrogen recombination line emission, and the molecular cloud traced by its CO($1 \rightarrow 0$) line emission. The FIR emission is spatially coincident with the [CII] (158 μm) fine structure line distribution. The [CII] line traces the photodissociated surfaces of molecular clouds, implying that the FIR continuum traces the structure of PDRs as well. The FIR [CII] and [OI] fine structure line work has shown that low metallicity can have a large effect on the structure of molecular clouds. For example, the CO emitting cores of such clouds is dramatically reduced relative to the photodissociated skins of the clouds. If the source is nearly edge-on, then the observed width of the FIR emission indicates relatively large PDRs, in agreement with these results.

We have used the 31.5 and 38 μm fluxes to derive a color temperature map of the region. The peak color temperature is 130 K, in fairly good agreement with the previous large beam work of Werner et al. (1978). If the source of the heating for the ridge is the R136 complex at its projected distance from the FIR peaks of 18 pc, then the observed color temperature is consistent with very small grains (~ 0.01 μm) as the source for the FIR emission. Curiously, however, our preliminary color temperature map shows little evidence for a color gradient from the R136 complex as one would expect for a centrally heated source. Perhaps the beam (~ 2 pc) is too large to reveal this gradient, or the source is not very close to edge on.

The KWIC grant produced one PhD: "High Spatial Resolution Mid and Far-Infrared Imaging of the Galactic Center" by Harri Michael Latvakoski, and has already or will soon result in over thirteen publications including:

"KWIC: A Widefield Mid-Infrared Array Camera/Spectrometer for the KAO" G. J. Stacey, T. L. Hayward, H. Latvakoski, & G. E. Gull, Infrared Detectors and. Instrumentation, SPIE Proceedings, 1946, 238 (1993).

"The Kuiper Widefield Infrared Camera (KWIC)", G. J. Stacey, T. L. Hayward, H. Latvakoski, L. Peng & G. E. Gull, in proceedings of the Second Cologne - Zermatt. Symposium on the Molecular Clouds, 362 (1995).

"The Kuiper Widefield Infrared Camera (KWIC)", H. Latvakoski, G.J. Stacey, T. L. Hayward, G.E. Gull, & L. Peng, in Proceedings of the Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust, ed. M.R. Haas, J.A. Davidson, & E.F. Erickson, (San Francisco: ASP), 539 (1995).

"KWIC Imaging of the Orion Nebula", G.J. Stacey, G.E. Gull, T.L. Hayward, H. Latvakoski & L. Peng, in Proceedings of the Airborne Astronomy Symposium on the. Galactic Ecosystem: From Gas to Stars to Dust, ed. M.R. Haas, J.A. Davidson, & E.F. Erickson, (San Francisco: ASP), 215 (1995).

"38 Micron Images of Galaxies: The Infrared Luminosity", G. J. Stacey, T. L. Hayward, G. E. Gull, & H. Latvakoski, in "New Extragalactic Perspectives in the New South Africa: Changing Perceptions of the Dust Content, and Dust to Gas Ratio in Galaxies", ed. D. Block (Kluwer Academic), 513 (1996).

"KWIC Imaging of the Galactic Center", H. M. Latvakoski, G. J. Stacey, T. L. Hayward, & G. E. Gull, in 4th ESO/CTIO Workshop: The Galactic Center, ed. R. Gredel (San. Francisco, ASP 102) 106, (1996).

"Kuiper Widefield Infrared Camera Far-Infrared Imaging of the Galactic Center: The Circumnuclear Disk Revealed", H.M. Latvakoski, G.J. Stacey, G.E. Gull, & T. Hayward, Ap.J. 511, 000 (1999).

"High Resolution Far-infrared Observations of the Galactic Center Arches: A Case for Internal Heating", H.M. Latvakoski, G.J. Stacey, G.E. Gull, & T. Hayward, submitted to ApJ (1999).

"Mid-Infrared Imaging of the Circumnuclear Ring: Clumps and Streamers at Arcsecond Resolution" H.M. Latvakoski, G.J. Stacey, G.E. Gull, & T. Hayward, to be submitted to ApJ (1999).

High Spatial Resolution Far-IR Imaging of the Orion Nebula: Clumps and Jets at the 0.02 pc Scale", G. J. Stacey, G. E. Gull, T. L. Hayward, H. Latvakoski, and L. Peng to be submitted to ApJ (1999).

"A Comprehensive KAO/ISO Far-Infrared Study of M82: Defining the Starburst", C.M. Bradford, H. Latvakoski, G. E. Gull, T. L. Hayward, L. Peng, and G. J. Stacey in prep.

"[SiII] Imaging of the Orion Nebula: Clumpy Structure of the Interface and a Dissociating Shock at KL" G. J. Stacey, G. E. Gull, T. L. Hayward, H. Latvakoski, and L. Peng in prep.

"Far-Infrared Imaging of the 30 Doradus Starformation Region" T. L. Hayward, G. E. Gull, H. Latvakoski, and G. J. Stacey in prep.

There were no inventions under this grant.

cc: 202-A-3