SUMMARY REPORT FOR NASA GRANT # NSG 2057, FAR-INFRARED ASTRONOMY WITH THE KUIPER AIRBORNE OBSERVATORY

Roger H. Hildebrand
Principal Investigator

Enrico Fermi Institute, Department of Physics, and
Department of Astronomy and Astrophysics
The University of Chicago

Period covered: December 1, 1974 to October 31, 1997

This report summarizes work made possible by NASA's Kuiper Airborne Observatory. The results of the work have appeared in over 80 papers (see attached list). The publications fall in three main areas: instrumentation, observations, and analysis. Although there is considerable overlap between these categories it will be convenient to group them separately.

1) Instrumentation

The first work under the grant was the introduction of non-imaging optics into far-infrared astronomy. The result was a significant improvement of the coupling of the incoming radiation to the detectors at the focal plane. To implement this type of optics it was necessary to develop designs for the light collectors, filters, and detector cavities. A succession of photometers incorporating the new optical techniques provided data not only for the Chicago group but also for many guest observers.

The next major effort was the development of instrumentation for far-infrared polarimetry. The basic design principle was to eliminate the effects of atmospheric fluctuations by simultaneous detection of two components of polarization. To apply the principle it was necessary to develop polarizing beam splitters, schemes for rotating the plane of polarization, and schemes to identify and remove systematic errors.

The polarimeters were then expanded to introduce detector arrays. This expansion required considerable redesign and revised techniques for removing the polarizing effects of the telescope and instrument. Like the photometers, the polarimeters have been used by ourselves and by many guest observers.

2) Observations

The first major application of the photometers was the determination of the far-infrared emissivity of interstellar dust. This made it possible to estimate the masses of interstellar clouds on the basis of the thermal emission (see item 3 below). Another important application resulted in the first detection of thermal emission from a Bok Globule and the subsequent discovery of embedded low-mass sources in several globules. Concurrent observations showed the existence of multiple cores in several giant molecular clouds.

Observations with the polarimeters showed that measureable polarization can be found in most regions of typical molecular clouds. The magnetic fields inferred from the polarization maps are surprisingly orderly and thus susceptible to theoretical analysis. There are examples of magnetically controlled star formation, of a torroidal field in the circumnuclear dust ring, of longitudinal fields in filaments, and of magnetic arcs around expanding shells of ionized material.

An archive of all airborne polarimetry is being prepared for publication in ApJ Supplements.

3) Reviews

Among various review papers we mention those in four main areas of research:

a) The early photometric work is summarized in a paper (Hildebrand 1983) reviewing the principles and techniques for measuring dust emissivities and thereby estimating cloud and dust masses.

b) The basic techniques used in both the photometers and the polarimeters are discussed in a paper on focal plane optics for far-infrared and submillimeter astronomy (Hildebrand 1986).

c) The principles governing polarized emission are presented in a paper on the interaction of magnetic fields and interstellar dust (Hildebrand 1988).

d) A model for "heterogeneous" molecular cloud envelopes is offered in a paper presenting the first results of spectropolarimetry in the far-infrared and submillimeter regions of the spectrum. This paper presents a review of the principles governing polarization spectra at long wavelengths (Hildebrand et al. 1998).

One result of the work under this grant has been to provide techniques and research objectives that can be pursued with SOFIA, NASA's next airborne observatory.

PAPERS SUPPORTED BY NASA GRANT # NSG 2057

Heat trap: an optimized far-infrared field optics system. D. A. Harper, R. H. Hildebrand,R. Stiening, and R. Winston. *Appl. Opt.* **15**, 53-59 and erratum p. 814 (January 1976). Reprinted in *Selected Papers on Nonimaging Optics,*, eds: R. Winston and B.J. Thompson (Bellingham: SPIE Optical Engineering Press) p. 48-55 (1995).

Far Infrared and Submillimeter Observations of the Planets. R. F. Loewenstein, D. A. Harper, S. H. Moseley, C. M. Telesco, H. A. Thronson, Jr., R. H. Hildebrand, S. E. Whitcomb, R. Winston, and R. F. Stiening. *Icarus* **31**, 315-324 (July 1977).

Submillimeter Photometry of Extragalactic Objects. R. H. Hildebrand, S. E. Whitcomb, R. Winston, R. F. Stiening, D. A. Harper, and S. H. Moseley. *Astrophys. J.* **216**, 698-705 (15 September 1977).

Submillimeter Observations of the Galactic Center. R. H. Hildebrand, S. E. Whitcomb, R. Winston, R. F. Stiening, D. A. Harper, and S. H. Moseley. *Astrophys. J. (Letters)* **219**, L101-L104 (1 February 1978).

Compact infrared heat trap field optics. J. Keene, R. H. Hildebrand, S. E. Whitcomb, and R. Winston. *Appl. Opt.* **17**, 1107-1109 (1 April 1978). Reprinted in *Selected Papers on Nonimaging Optics,*, eds: R. Winston and B.J. Thompson (Bellingham: SPIE Optical Engineering Press) p. 154-156 (1995).

Submillimeter Brightness Temperatures of Venus, Jupiter, Uranus, and Neptune. S. E. Whitcomb, R. H. Hildebrand, J. Keene, R. F. Stiening, and D. A. Harper. *Icarus* **38**, 75-80 (April 1979).

Millimetre and Submillimetre Measurements of the Crab Nebula. E. L. Wright, D. A. Harper, R. H. Hildebrand, J. Keene, and S. E. Whitcomb. *Nature* **279**, 703-705 (21 June 1979).

Changes in the Rapid Oscillations of AH Herculis During an Outburst. R. F. Stiening, R. H. Hildebrand, and E. J. Spillar. *Pub. Astron. Soc. Pac.* **91**, 384-388 (June 1979).

The Evolution of Rapid Oscillations in an Outburst of a Dwarf Nova. R. H. Hildebrand, E. J. Spillar, J. Middleditch, J. J. Patterson, and R. F. Stiening. *Astrophys. J. (Letters* **238**, L145-L148 (15 June 1980).

Far-Infrared Observations of the Globule B335. J. Keene, D. A. Harper, R. H. Hildebrand, and S. E. Whitcomb. *Astrophys. J. (Letters)* **240**, L43-L46 (15 August 1980).

Far-Infrared Photometry of Titan and Iapetus. R. F. Loewenstein, D. A. Harper, R. H. Hildebrand, S. H. Moseley, E. Shaya, and J. Smith. *Icarus* **43**, 283-287 (September 1980).

Brightness Temperatures of Saturn's Disk and Rings at 400 and 700 Micrometers. S. E. Whitcomb, R. H. Hildebrand, and J. Keene. *Science* **210**, 788-789 (14 November 1980).

An f/35 Submillimeter Photometer for the NASA Infrared Telescope Facility. S. E. Whitcomb, R. H. Hildebrand, and J. Keene. *Publ. Astron. Soc. Pac.* **92**, 863-869 (December 1980).

Observations of Fast Oscillations in SS Cygni. R. H. Hildebrand, E. J. Spillar, and R. F. Stiening. *Astrophys. J.* **243**, 223-227 (1 January 1981).

Far-Infrared Observations of the Cepheus OB3 Molecular Cloud. N. J. Evans II, E. E. Becklin, C. Beichman, I. Gatley, R. H. Hildebrand, J. Keene, M. H. Slovak, M. W. Werner, S. E. Whitcomb. *Astrophys. J.* **244**, 115-123 (15 February 1981).

Far-Infrared Properties of Dust in the Reflection Nebula NGC 7023. S. E. Whitcomb, I. Gatley, R. H. Hildebrand, J. Keene, K. Sellgren, and M. W. Werner. *Astrophys. J.* **246**, 416-425 (1 June 1981).

The Color of the Fast Oscillations of AH Herculis. R. H. Hildebrand, E. J. Spillar, and R. F. Stiening. *Astrophys. J.* **248**, 268-273 (15 August 1981).

Solar Limb Brightening at 350 Microns. C. Lindsey, R. H. Hildebrand, J. Keene, and S. E. Whitcomb. *Astrophys. J.* **248**, 830-835 (1 September 1981).

A High Resolution Submillimeter Map of OMC-1. J. Keene, R. H. Hildebrand, and S. E. Whitcomb. *Astrophys. J. (Letters)* **252**, L11-L15 (1 January 1982).

Throughput of diffraction-limited field optics systems for infrared and millimetric telescopes. R. H. Hildebrand and R. Winston. *Appl. Opt.* **21**, 1844-1846 (15 May 1982). (See errata. Ibid. **24**, No. 5, 616 (1 March 1985). Reprinted with corrections and revisions in *Selected Papers on Nonimaging Optics*,, eds: R. Winston and B.J. Thompson (Bellingham: SPIE Optical Engineering Press) p. 309-311 (1995).

415 μm Brightness Temperature of Titan. R. F. Loewenstein and R. H. Hildebrand. *Astron. and Astrophys.* **110**, L18-L19 (June 1982).

Observations of Rapid Oscillations in EM Cygni. R. F. Stiening, M. Dragovan, and R. H. Hildebrand. *Publ. Astron. Soc. Pac.* **94**, 672-677 (August 1982).

New Far-Infrared Observations of the Central 30' of the Galaxy. W. A. Dent, M. W. Werner, I. Gatley, E. E. Becklin, R. H. Hildebrand, J. Keene, and S. E. Whitcomb. *AIP Conf. Proc.,The Galactic Center*, No. **83**, 33-41, eds. G. R. Riegler and R. D. Blandford (1982).

The Determination of Cloud Masses and Dust Characteristics from Submillimeter Thermal Emission. R. H. Hildebrand. *Q. J. R. Astron. Soc.*, **24**, 267-282 (September 1983).

Submillimeter Observations of W3. D. T. Jaffe, R. H. Hildebrand, J. Keene, S. E. Whitcomb. *Astrophys. J. Lett.*,**273**, L89-L93 (15 October 1983).

Far-Infrared Detection of Low-Luminosity Star Formation in the Bok Globule B335. J. Keene, J. A. Davidson, D. A. Harper, R. H. Hildebrand, D. T. Jaffe, R. F. Loewenstein, F. Low, and R. Pernic. *Astrophys. J. Lett.*, **274**, L43-L47 (1 November 1983).

Far-Infrared and Submillimeter Observations of the Low-Luminosity Protostars L1455 FIR and L1551 IRS5: The Confinement of Bipolar Outflows. J. A. Davidson and D. T. Jaffe. *Astrophys. J. Lett.*, **277**, L13-L16 (1 February 1984).

A Gold Absorbing Film for a Composite Bolometer. M. Dragovan and S. H. Moseley. *Appl. Opt.*, **23**, 654-656 (1 March 1984).

The Massive Core of W51. D. T. Jaffe, E. E. Becklin, and R. H. Hildebrand. *Astrophys. J. Lett.*, **279**, L51-L54 (15 April 1984).

Far-Infrared Selected Star Formation Regions. D. T. Jaffe, R. H. Hildebrand, J. Keene, D. A. Harper, R. F. Loewenstein, and J. Moran. *Astrophys. J.*, **281**, 225-236 (1 June 1984).

First Results of Submillimeter Polarimetry. R. H. Hildebrand, M. Dragovan, and G. Novak. *Proc. 1984 Airborne Astronomy Symposium*, Ames Res. Ctr. NASA Conf. Publ. **2353**, 134-139, eds. H. A. Thronson and E. F. Erickson (11 July 1984).

Star Formation in Globules. J. A. Davidson. *Proc. 1984 Airborne Astronomy Symposium*, Ames Res. Ctr., NASA Conf.Publ. **2353**, 186-193, eds. H. A. Thronson and E. F. Erickson (11 July 1984).

Instrumentation for Submillimeter Polarimetry. M. Dragovan and G. Novak. *Proc. 1984 Airborne Astronomy Symposium*, Ames Res. Ctr., NASA Conf. Publ. **2353**, 335-340, eds. H. A. Thronson and E. F. Erickson (11 July 1984).

Cryogenic Metal Mesh Bandpass Filters for Submillimeter Astronomy. M. Dragovan. *Appl. Opt.*, **23**, 2798-2802 (15 August 1984).

Far-IR and Submillimeter Observations of the Multiple Cores in S255, W3,and OMC-1: Evidence for Fragmentation? D. T. Jaffe, J. A. Davidson, M. Dragovan, and R. H. Hildebrand. *Astrophys. J.*, **284**, 637-642 (15 September 1984).

Detection of Submillimeter Polarization in the Orion Nebula. R. H. Hildebrand, M. Dragovan, and G. Novak. *Astrophys. J. Lett.*, **284**, L51-L54 (15 September 1984).

Submillimeter Continuum Observations of M82. D. T. Jaffe, E. E. Becklin, and R. H. Hildebrand. *Astrophys. J. Lett.*, **285**, L31-L33 (1 October 1984)

On the Nature of the Material Surrounding Vega. D. A. Harper, R. F. Loewenstein, and J. A. Davidson. *Astrophys. J.*, **285**, 808-812 (15 October 1984).

The Resonant Bolometer: Results and Applications. M. Dragovan and S. H. Moseley. *Appl. Opt.*, **24**, 1770 (15 June 1985).

Submillimeter Observations of Evolved Stars. R. J. Sopka, R. H. Hildebrand, D. T. Jaffe, I. Gatley, T. Roellig, M. Werner, M. Jura, and B. Zuckerman. *Astrophys. J.*, **294**, 242-255 (1 July 1985).

Exploration of Molecular Clouds by Submillimeter Photometry. R. H. Hildebrand. *National Geographic Society Research Reports*, **20**, 365-371(1985).

Far-Infrared and Submillimeter Brightness Temperatures of the Giant Planets. R. H. Hildebrand, R. F. Loewenstein, D. A. Harper, G. S. Orton, J. Keene, and S. E. Whitcomb. *Icarus*, **64**, 64-87 (1985).

Focal Plane Optics in Far-Infrared and Submillimeter Astronomy. R. H. Hildebrand. *Opt. Eng .*, **25**, 323-330 (February 1986).

The Orion Star-Forming Region: Far-Infrared and Radio Molecular Observations. H. A. Thronson, Jr., D. A. Harper, J. Bally, M. Dragovan, D. Mosurkewich, M. A. Greenhouse, P. R. Schwartz, H. A., Smith, J. H. Bieging, R. F. Loewenstein, and C. J. Lada. *Astron. J.*, **91**, 1350-1356 (June 1986).

Submillimeter Polarization in the Orion Nebula. M. Dragovan. *Astrophys. J.*, **308**, 270-280, (1 September 1986).

Low Luminosity Embedded Sources and Their Environs. J. A. Davidson. *Astrophys. J.*, **315**, 602-620 (15 April 1987).

Magnetic Alignment of Grains. R. H. Hildebrand. *Astro. Lett. and Communications*, **26**, 263-275 (1988).

Magnetic Fields and Stardust. R. H. Hildebrand. *Q. Jl. R. astr. Soc.*, **29**, 327-351(Sept.1988).

The Polarization of the Far-infrared Radiation from the Galactic Center. M. W. Werner, J. A. Davidson, M. Morris, G. Novak, S. R. Platt, and R. H. Hildebrand. *Astrophys. J.*, **333**, 729-734 (15 October 1988).

A 100 μm Polarimeter for the Kuiper Airborne Obsevatory. G. Novak, D. P. Gonatas, R. H. Hildebrand, and S. R. Platt. *Publ. Astron. Soc. Pac.*, **101**, 215-224 (February 1989).

Far-Infrared and Submillimeter Photometric Mapping of Spiral Galaxies in the Virgo Cluster. A. A. Stark, J. A. Davidson, S. Platt, D. A. Harper, R. Pernic, R. Loewenstein, G. Engargiola, S. Casey. *Astrophys. J.*, **337**, 650, (15 February 1989).

Systematic Effects in the Measurement of Far-infrared Linear Polarization. D. P. Gonatas, X. D. Wu, G. Novak, and R. H. Hildebrand. *Applied Optics*, **28**, 1000-1006 (1 March 1989).

Far-infrared Polarizing Grids for use at Cryogenic Temperatures. G. Novak, R. Pernic, and J. Sundwall. *Applied Optics*, **28**, 3425 (15 August 1989).

Polarized Infrared Emission from Dust. R. H. Hildebrand. In *Interstellar Dust*, IAU Symposium No. 135, eds. L. J. Allamandola and A. G. G. M. Tielens, Dordrecht: Kluwer, p. 275 (1989).

Polarization of Far-Infrared Radiation from Molecular Clouds. G. Novak, D. P. Gonatas, R. H. Hildebrand, S. R. Platt, and M. Dragovan. *Astrophys. J.*, **345**, 802 (15 October 1989).

The Magnetic Field at the Center of the Galaxy. R. H. Hildebrand. In *Submllimetre Astronomy*, eds. G. D. Watt and A. S. Webster, Dordrecht: Kluwer, 25-27 (1990).

Far Infrared Polarization of the Orion Nebula. D. P. Gonatas, G. A. Engargiola, R. H. Hildebrand, S. R. Platt, X. D. Wu, J. A. Davidson, G. Novak, D. K. Aitken, C. Smith. *Astrophys. J.*, **357**, 132-137 (1990).

The Magnetic Field in the Dust Ring at the Center of the Galaxy. R. H. Hildebrand, D. P. Gonatas, S. R. Platt, X. D. Wu, J. A. Davidson, M. W. Werner, G. Novak, M. Morris. *Astrophys. J.*, **362**, 114-119 (10 Oct.1990).

SOFIA: The Stratospheric Observatory for Infrared Astronomy. R. H. Hildebrand and J. A. Davidson. in *From Ground-Based to Space-Based Sub-mm Astronomy*, p. 135-139, Proc. 29th Interntl. Astrophys. Coll., Institut d'Astrophysique, Liege, 3-5 July (1990).

100 μm Array Polarimetry from the Kuiper Airborne Observatory: Instrumentation, Techniques, and First Results. S. R. Platt, R. H. Hildebrand, R. J. Pernic, J. A. Davidson,and G. Novak. *Publ. Astron. Soc. Pac.*, **103**, 1193-1210 (Nov.1991).

High-Resolution Imaging of the Galactic Cloud Monoceros R2. C. P. Gonatas, P. Palmer, and G. Novak. *Ap. J.*, **398**, 118-127, (10 Oct.1992).

Polarization of the Far-Infrared Emission from the Thermal Filaments of the Galactic Center Arc. M. Morris, J. A. Davidson, M. Werner, J. Dotson, D. F. Figer, R. H. Hildebrand, G. Novak, and S. R. Platt. *Ap. J.*, **399**, L63-L66 (1 Nov. 1992).

Polarization of the Thermal Emission from the Dust Ring at the Center of the Galaxy. R. H. Hildebrand, J. A. Davidson, J. Dotson, D. F. Figer, G. Novak, S. R. Platt, and L. Tao *Ap. J.* **417**, 565 (10 Nov. 1993).

The Magnetic Field in the Dust Ring and Northern Arm of Sgr A West. R. H. Hildebrand and J. A. Davidson. In *The Nuclei of Normal Galaxies.* eds. R. Genzel & A.I.Harris, Dordrecht: Kluwer, p.199-203 (1994).

Far-Infrared Polarimetry. R. H. Hildebrand, J. L. Dotson, C. D. Dowell, S. R. Platt, D. Schleuning, J. A. Davidson, & G. Novak. In *Proc. of the Airborne Astronomy Symp πon the Galactic Ecosystem: From Gas to Stars to Dust*, ed. M.R. Haas, J.A. Davidson, & E.F. Erickson (San Francisco: ASP), p. 97 (1995).

The Magnetic Field Structure in High-Mass Star Formation Regions. J.A. Davidson, D. Schleuning, J.L. Dotson, C.D. Dowell, & R.H. Hildebrand. In *Proc. of the Airborne Astronomy Symp on the Galactic Ecosystem: From Gas to Stars to Dust*, ed. M.R. Haas, J.A. Davidson, & E.F. Erickson (San Francisco: ASP), p. 225 (1995).

Stokes, the Chicago Far-Infrared Polarimeter. S. R. Platt, J. L. Dotson, C. D. Dowell, R. H. Hildebrand, G. Novak, & D. Schleuning. In *Proc. of the Airborne Astronomy Symp on the Galactic Ecosystem: From Gas to Stars to Dust*, ed. M.R. Haas, J.A. Davidson, & E.F. Erickson (San Francisco: ASP), p. 543 (1995).

The Shapes and Alignment Properites of Interstellar Dust Grains. R. H. Hildebrand, & M. Dragovan. ApJ. 450, 663 (1995).

Array Polarimetry of the Orion Nebula from the Caltech Submillimeter Observatory. D.A. Schleuning, C. D. Dowell, & S. R. Platt. In *Polarimertry of the Interstellar Medium,* eds. W. G. Roberge & D. C. B. Whittet, ASP Conference Series San Francisco. p.285-289 (1996).

Problems in Far-Infrared Polarimetry. R. H. Hildebrand. In *Polarimertry of the Interstellar Medium,* eds. W. G. Roberge & D. C. B. Whittet, ASP Conference Series, vol. 97. San Francisco. p 254 - 268 (1996).

Polarization of the Far-Infrared Emission of M17. J. L. Dotson. 1996. ApJ. 470: 566-576 (1996).

Hertz, A Submillimeter Polarimeter. D. A. Schleuning, C. D. Dowell, R. H. Hildebrand, & S. R. Platt. PASP 109:307-318 (1997).

Far-Infrared Polarization by Absorption in the Molecular Cloud Sagittarius B2. C. D. Dowell. ApJ. 487, 237-247(1997).

Polarized Far-Infrared Emission from the core and envelope of the Sagittarius B2 Molecular Cloud, G. Novak, J. L. Dotson, C. D. Dowell, P. F. Goldsmith, R. H. Hildebrand, S. R. Platt, & D. A. Schleuning. ApJ. 487, 320-327 (1997).

Hertz, A Submillimeter Polarimeter. D. A. Schleuning, C. D. Dowell, R. H. Hildebrand, & S. R. Platt. PASP 109:307-318 (1997).

Far-Infrared and Submillimeter Polarization of OMC-1 - Evidence for Magnetically Regulated Star Formation. D.A. Schleuning. ApJ 493, 811-825 (1997).

Submillimeter Polarimetry of Sagittarius A. G, Novak, J. L. Dotson, T.Renbarger, C. D. Dowell, R. H.Hildebrand, & D. A. Schleuning, in Proceedings of IAU Symposium #184 on "The Central Regions of the Galaxy and Galaxies", Kyoto, Japan, August 1997. ASP, San Francisco

Hertz, an Imaging Polarimeter, R. H. Hildebrand, J. L. Dotson, C. D. Dowell, G. Novak, D. A. Schleuning, and J. Vaillancourt. SPIE International Symposium on Astronomical Telescopes and Instrumentation, 1998. In press

Polarized Far-Infrared Emission from the Core and Envelope of the Sagittarious B2 MolecularCloud. G. Novak, J.L. Dotson, C.D. Dowell, P.F. Goldsmith, R H. Hildebrand, S.R. Platt, & D.A. Schleuning. ApJ. 487, 320-327 (1997).

Submillimeter Polarimetry of Sagittarius A. G. Novak, J. L. Dotson, T. Renbarger, C. D. Dowell, R. H. Hildebrand, & D.A, in Proceedings of IAU Symposium #184 on "The Central Regions of the Galaxy and galaxies, ed. Y. Sofue (Kluwer, Dordrecht), ASP San Francisco, (1998).

Hertz, an Imaging Polarimeter. R.H. Hildebrand. J. L. Dotson, C.D. Dowell, D.A. Schleuning, & J. Vaillancourt, in SPIE International Symposium on Astronomical Telescopes and Instrumentation, (1998).

Submillimeter Array Polarimeter with Hertz, C.D. Dowell, R.H. Hildebrand,D.A. Schleuning, J.L. Dotson, G. Novak, T. Renbarger, & M. Houde, ApJ. Sept. 1 (1998).

Submillimeter Polarimetric Observations of the Galactic Center. G, Novak, J. L. Dotson, C. D. Dowell, R. H.Hildebrand, T. Renbarger, & D. A. Schleuning. Submitted to ApJ. (1998).

Summary of Results from Far-Infrared Polarimetry. J. L. Dotson, C. D. Dowell, D. A. Schleuning, & R. H. Hildebrand. To be submitted to ApJ (Suppl.) (1998).

First Results of Spectropolarimetry at 60 μm to 350 μm. R.H. Hildebrand, J. L. Dotson, C. D. Dowell, D.A. Schleuning, and J.E. Vaillancourt. To be submitted to ApJ (1998)

Far-Infrared and Submillimeter Polarization of the W3 Molecular Cloud. D.A. Schleuning, J.E. Vaillancourt, R.H. Hildebrand, C.D. Dowell, G. Novak, J.L. Dotson, and J.A. Davidson. To be submitted to ApJ,. (1998).