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SOFIA - A Stratospheric Observatory for Infrared Astronomy

E. F. Erickson, J. A. Davidson, G. Thorley,
and L. J. Caroff

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SOFIA

STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY

June 1991

FOREWORD

This document was originally prepared to describe SOFIA – the Stratospheric Observatory for Infrared Astronomy – for the Space and Earth Sciences Advisory Committee (SESAC) in May 1988. SESAC reported to Dr. Lennard Fisk, the NASA Associate Administrator who heads the Office of Space Science and Applications. The format and the questions answered in the report were provided by SESAC as a standard for judging the merit of potential U.S. space science projects. The report was updated in May 1991 for the Space Science and Applications Advisory Committee (SSAAC), which has superseded the SESAC.

Several other projects are mentioned in the document by their acronyms. These are familiar to the space science community, but are given here (in approximate chronological order by mission commencement) for completeness. Only the KAO, IRAS, COBE, HST and GRO have flown.

Acronym	Name	Wavelengths
KAO	Kuiper Airborne Observatory	near UV, optical, IR, FIR, submm
IRAS	Infrared Astronomical Satellite	FIR
HST	Hubble Space Telescope	UV, optical
COBE	Cosmic Background Explorer	FIR, submm, mm
GRO	Gamma Ray Observatory	gamma rays
ISO*	Infrared Space Observatory	IR, FIR, submm
AXAF	Advanced X Ray Facility	X rays
SIRTF	Space Infrared Telescope Facility	IR, FIR, submm
FIRST*	Far-Infrared and Submillimeter Telescope	FIR, submm
LDR	Large Deployable Reflector	FIR, submm

Here UV refers to ultraviolet, IR to infrared, FIR to far-infrared, submm to sub-millimeter, and mm to millimeter. Roughly the IR corresponds to wavelengths from 1 to 10 microns (abbreviated μm), FIR from 10 to 100 μm, submm from 100 μm to 1 mm, and mm from 1 to 10 mm. The asterisks indicate projects being sponsored by the European Space Agency.

In the report we describe SOFIA's unique astronomical potential, and show how it complements and supports these existing and planned facilities.

ACKNOWLEDGEMENTS

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E. F. Erickson, J. A. Davidson, G. Thorley
NASA Ames Research Center

L. J. Caroff
NASA Headquarters

SOFIA
A Stratospheric Observatory For Infrared Astronomy

OVERVIEW

SOFIA will be an airborne observatory designed to address fundamental questions in galactic and extragalactic astronomy and in the origin and evolution of the Solar System. Much of the radiant energy in the Universe lies at infrared wavelengths which are not observable from ground-based telescopes. SOFIA will provide ready and frequent access to these wavelengths with excellent spatial and spectral resolution.

SOFIA will succeed the Kuiper Airborne Observatory (KAO), which has been in continuous successful operation since 1975, and which has produced a wealth of significant astronomical results. Like the KAO, SOFIA will operate in the low stratosphere where absorption by telluric water vapor is greatly reduced. Figure 1 compares the atmospheric transmission from aircraft altitudes to that from Mauna Kea, the best ground-based infrared site. Clearly much of the radiation from astronomical objects which never reaches earth is readily observable from aircraft.

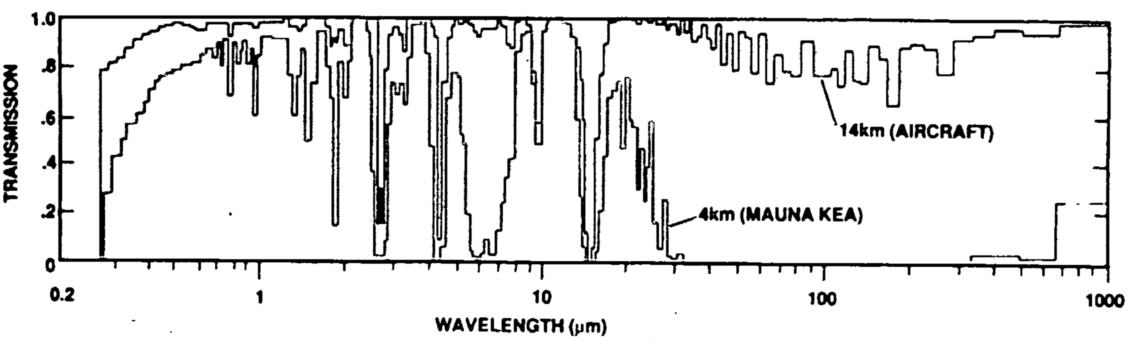

Figure 1. Atmospheric transmission versus wavelength.

The transmissions plotted in Figure 1 are for broad band-passes. Where the transmission is low the emissivity is high. Low transmission reduces the signal from the source, and high emissivity increases detector noise due to fluctuations in the arrival rate of photons from the sky background. This explains why much higher photometric sensitivity can be achieved by a space-based cryogenic telescope, such as SIRTF, than by telescopes which must view through the atmosphere. On the other hand, at high spectral resolution – when the detector sees between individual atmospheric absorption lines – the sky emissivity can be quite low at aircraft altitudes, so that an airborne spectrometer can achieve sensitivity limited principally by the emission of the telescope.

For some 25 years, and most recently with the KAO, astronomers have exploited the improved transmission of the atmosphere at aircraft altitudes depicted in Figure 1. SOFIA, however, will greatly extend our capabilities beyond those of the KAO, assuring continued preeminence of the United States in airborne astronomy. SOFIA will have roughly 3 times the angular resolution and 10 times the point source sensitivity of the KAO. The increased sensitivity will also permit significantly increased spectral resolution to be achieved on compact sources.

Observations throughout the infrared and sub-millimeter provide a particularly effective tool for studying a wide range of astronomical phenomena. This is so because: (1) Such diverse objects as molecular clouds, pre-planetary disks, solar system bodies, and many galaxies have their peak emission in the infrared; (2) Infrared radiation can penetrate dusty regions in our Galaxy and other galaxies to reveal sources and phenomena which are completely obscured at optical and even near-infrared wavelengths; and (3) Many molecular, atomic, and ionic species abundant in circumstellar and interstellar environments have their characteristic spectral transitions in the infrared and sub-millimeter wavelength regions.

Among the primary science goals of SOFIA is a detailed and comprehensive study of the steps and processes which lead from cold clouds in the Interstellar Medium (ISM), through the formation and evolution of stars and planetary systems, to the eventual return of processed material to the ISM. SOFIA will also turn its superior spatial and spectral resolution to the examination of dust and gas in the vicinity of our Galactic Center, to search for the signature of a massive black hole which may be the central powerhouse of the Galaxy. On still larger scales, SOFIA will provide new understanding of the ultra-high luminosity infrared-emitting galaxies discovered by IRAS. In addition, the unique mobility of an airborne observatory allows effective response to a number of highly localized and sometimes quite transient phenomena, such as solar eclipses, comets, novae, supernovae, and stellar occultations by solar system bodies.

To accomplish these goals, SOFIA will consist of a 2.5 meter, open-port telescope in a Boeing 747 airplane, providing continuous in-flight access to focal plane instruments by participating astronomers. The KAO has proven the feasibility of high quality airborne observations and SOFIA will build on this heritage. Although technically challenging, SOFIA will require innovative engineering rather than new technology to achieve the required performance.

SOFIA will be a joint project under U.S. leadership with the Federal Republic of Germany supplying the telescope assembly and participating in the flight program. SOFIA's 20 year lifetime will provide a foundation of research, instrument development, and training of young scientists, bridging the gap between IRAS and SIRTF, and providing continuity in infrared astronomy into the era of FIRST and LDR. Its excellent spatial and spectral resolution will complement SIRTF's extraordinary sensitivity, and its wavelength coverage assures complementary support for HST, GRO, and AXAF. SOFIA will be a unique and important element in the U.S. space astronomy program.

SUMMARY OF BASIC SOFIA CHARACTERISTICS

In-flight access to focal plane instruments – continuous
Operating altitudes – 41,000 to 45,000 feet
Aircraft-limited duration at or above 41,000 feet ≥ 5 hours
Nominal flight duration (crew-limited) – 7.5 hours
Research flights per year – ~ 120
Number of principal investigator teams flown per year – ~ 40
Number of focal plane instruments flown per year – ~ 20
Vehicle – Boeing 747 SP
Stabilized telescope system weight – ~ 16,000 kg
Primary mirror diameter – ~ 2.5 meters
Wavelength range – 0.3 to 1600 μm
Telescope configuration – Nasmyth
Design f/ ratio – ~ 20
Unvignetted field of view – 8 arcminutes
Telescope-system visible image quality ≲ 1.5 arcseconds
Shear layer seeing - 2-3 arcseconds @ 5 microns; 4-6 arcseconds @ visible λ
Diffraction-limited at wavelengths – ≳ 15 μm
RMS pointing stability – 0.2 arcseconds
Telescope emissivity – 15%
Nominal operating optics temperature – ~ 240K

I. SCIENTIFIC MERIT

A. SCIENTIFIC OBJECTIVES AND SIGNIFICANCE

1. WHAT ARE THE KEY SCIENTIFIC ISSUES BEING ADDRESSED BY SOFIA?

SOFIA will be a unique observatory with an evolving complement of state-of-the-art instruments and a 20 year lifetime. As such it will address a wide range of scientific problems crossing a number of disciplines and subdisciplines. Central to these scientific issues will be the investigation of the formation and evolution of stars and stellar systems in the Galaxy and in external galaxies, the formation and evolution of preplanetary disks, and the detailed study of the Solar System and its environment. Many of SOFIA's primary science goals involve the study of the Interstellar Medium (ISM) and its role in the life cycles of stars and galaxies.

2. HOW SIGNIFICANT ARE THESE ISSUES IN THE CONTEXT OF SCIENCE?

The central goals of astronomy include understanding the structure and evolution of the Universe, the origin and evolution of galaxies, stars, and planetary systems, and the conditions which lead to the origin of life. These issues are fundamental ones for science in general. SOFIA will directly address a number of them: the formation of stars, planets, and biogenic materials.

3. TO WHAT EXTENT IS SOFIA EXPECTED TO RESOLVE THEM?

Stars and protoplanetary systems are born from the collapse of clouds of gas and dust in the Interstellar Medium. Planets, in turn, are thought to grow through the coagulation of grains in the protoplanetary disk around a young star due to gravitational instabilities. The heavy element abundances in the initial interstellar cloud determine the nature of the formation process and the chemical composition of the newly-formed stars and planets. The abundances of the elements in the ISM change with time as dying stars return processed material to the Galaxy, enriching the ISM with the elements required to form and sustain life. SOFIA will provide the fundamental capability to study this *entire cycle* and return unique information which will not be obtainable by any other means over the next two decades.

(i) The Interstellar Medium:

All galaxies are permeated by an Interstellar Medium, but with properties which may vary greatly from galaxy to galaxy. Fundamental phases of the ISM – solids, molecular gas, neutral atomic gas, and ionized gas – are characterized by infrared, far-infrared, or sub-millimeter emission. Observations of the ISM are critical to the study of the cycle of gestation, birth, evolution, and death of stars mentioned above for the following reasons:

(a) The composition of the ISM determines the chemical makeup of the objects which form from it; (b) The structure and physical state of the ISM in a particular region determine the nature of subsequent evolution there, for example in the formation of high mass versus low mass stars; and (c) Interesting phenomena are often embedded in dense, dusty regions of the ISM and can only be observed indirectly through the interaction of the source with the ISM. Therefore an understanding of the properties of the ISM is essential to interpret observations of the embedded sources correctly.

From SOFIA, astronomers would map with high spatial resolution the total and polarized thermal continuum from cool dust in molecular clouds, as well as the corresponding power radiated in atomic fine structure and rotational molecular lines. These measurements provide estimates of the density, luminosity, temperature, chemical and dust grain makeup, magnetic fields, and detailed morphology of these regions.

Carbon chemistry is the basis of life as we know it, and has its beginnings in the ISM. Carbon emission lines also provide a large percentage of gas cooling in the ISM, thus altering the ISM environment and subsequent chemical evolution. Spectroscopy will yield particularly significant results on carbon chemistry in clouds, via the 158 μm C^+ line, the 370 and 609 μm C lines, and a host of far-infrared and sub-millimeter rotational CO lines. As an example, Figure 2 shows a KAO measurement of the C^+ line from NGC 2024, a molecular cloud/ionized gas complex, obtained with a velocity resolution of 1 km/s. Line observations at such high spectral resolution provide information on systematic and turbulent motions within a cloud. SOFIA's spatial resolution will allow study of the process of cloud fragmentation in clumps as small as one solar mass.

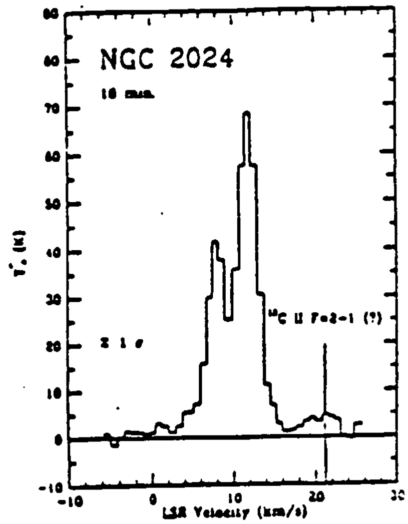

Figure 2. Velocity resolved spectrum of C^+ at 158 μm

(ii) Star Formation:

The ubiquitous associations of young stars with dark clouds clearly tells us that star formation occurs in dense regions of the ISM. The star formation process is not well understood. For example, it is not known why or when a region of a cloud will start to collapse. In order to form a one solar mass star, the collapse must extend to a radius of about 10^{17} cm in a quasi-stable dense clump in an interstellar cloud. This distance would correspond to just under an arcminute on the sky if we were observing the collapse in the nearest star formation region, the Taurus cloud, which is 160 pc away. The radiation from the star formation region in its early stages of evolution would be dominated by an accretion shock around the small protostar, and would peak in the far-infrared due to the large dust opacity in the surrounding cloud.

A number of IRAS point sources have been studied from the KAO and have been shown to be visibly obscured young stellar objects (YSO's). The improved spatial resolution of the KAO over IRAS has allowed determination of the mean densities and temperatures of the infall regions and star formation environments. SOFIA's much higher sensitivity and spatial resolution will enable us to make detailed maps of the infall regions and their envelopes. Knowledge of the mass and velocity structure of these regions places fundamental constraints on star formation theories. Such imaging ability is especially important because star formation is probably highly asymmetrical in the presence of rotation, causing the accreting material to form a circumstellar disk as well as a central protostar. The circumstellar disk would be hidden from view during accretion by the natal cloud. However, SOFIA will be able to map out the asymmetries of the infall region which cause the disk to form, and will allow us to detect and study the physics of protostars at earlier stages of evolution than is now possible.

In massive clouds, stars often form in clusters where currently we cannot separate the individual YSO's. Many of these could be isolated in the beam of SOFIA so that, for example, their individual masses and motions relative to one another could be determined. This would help us understand the process of fragmentation of large clouds to form star clusters.

(iii) Bipolar Outflows:

Theoretical models of star formation do not provide a complete account of the evolution of the protostar/disk system. For example, they are unable to predict the mechanism that causes accretion to cease. To date, theories have predicted only infall motions. However, since the early 1980's, observations have shown that many embedded YSO's are associated with powerful bipolar outflows. The mechanism which drives these outflows is so far a complete mystery. However, the theories do make predictions, as yet unverified but observable from SOFIA. For example, with SOFIA we can show at what stage in the evolution of a star the outflows "turn on," by mapping the infall regions of both the YSO's that do and those that do not have outflows. Far-infrared polarimetry of the infall regions from SOFIA will show, in the more luminous cases, the association between magnetic fields and the outflows.

(iv) Circumstellar Disks:

Little is known about circumstellar disks around T Tauri stars, which are thought to be typical, very young stars with masses comparable to that of our Sun. These stars and presumably their disks are formed in obscuring parent clouds. It is thought that the outflows mentioned above, although not understood, could eventually halt the disk accretion. The outflows could also dissipate the surrounding cloud, making the YSO's eventually visible as T Tauri stars. At a later evolutionary stage the disks will be dissipated or fragment, and there will be considerable disk clearing. Theoretical models of these disks predict that early in their evolution their continuum thermal emission should peak in the far-infrared, and in fact broad-band photometric measurements of their spectra from 50 to 300 μm can discriminate between some models of disk formation, implying a major role for SOFIA in their study. The models also predict that 63 μm O I emission produced by shockwaves set up in the disks by accreting material should be detectable from SOFIA as well. A key quantity of interest at this stage of the disk's development is its mass, knowledge of which would permit estimation of the fraction of matter that was accreted onto the disk versus the protostar. Such an estimate would considerably constrain star formation theories, and may be obtained from measurements of thermal emission by dust in the disk or by spectroscopic observations of gas motions in the disk. Observations of T Tauri stars have shown indirectly that if circumstellar disks do exist around these stars then they are generally not much more than 100 AU in diameter – comparable to the size of the solar system – or about 0.6 arcsec at 160 pc. However, HL Tau has been observed at millimeter wavelengths to have a dim 4000 AU (or 24 arcsecond) diameter disk, and observations from the KAO show extended emission associated with several T Tauris, for example SVS 13 shown in Figure 3. Thus at an early stage of their evolution, these disks may be sufficiently extended to be imaged directly at far-infrared wavelengths from SOFIA, which would be an exciting and extremely important input to theoretical understanding of low-mass star formation.

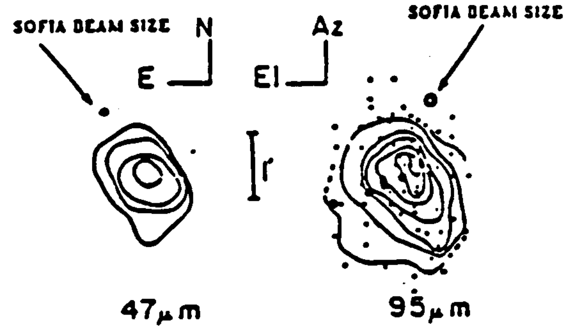

Figure 3. Far-infrared maps of thermal emission from SVS 13.

At later stages of circumstellar disk evolution, when planets are forming, the disks are harder to see. However, there are ~ 50 candidates for evolved stars with disks which are on the order of 20 times closer to Earth than the nearest T Tauri star, and at their distances 100 AU in the disk corresponds to 10-15 arcsec on the sky. Hence the spatial resolving power and sensitivity of SOFIA will allow direct imaging of the structure of these disks for the first time in the far-infrared. For example, Beta Pictoris ("β Pic") is a main-sequence star that is 17 pc away from Earth with an infrared-luminous disk discovered by

IRAS. The infrared disk diameter is ~ 2400 AU, or 140 arcseconds, with the bulk of the infrared flux coming from the central 30 arcseconds. The total IRAS 60 μm flux of the disk, when distributed into 5 arcsecond diameter pixels – the resolution of SOFIA at 60 μm – will require less than 30 minutes of integration on SOFIA for a signal to noise ratio of 10. It will be possible, therefore, to determine the disk temperature profile and morphology. Combining these results with the knowledge of the illuminating star, β Pic, will enable the properties of the dust in the disk to be studied, in particular the dust-grain size distribution. Figure 4 shows the visible β Pic system with the 5 arcsecond diameter, 60 μm SOFIA beam. The properties of the dust are important since it is probably from these particles that the cores of planets may eventually form, if not in the β Pic system, then in similar clouds around other stars. SOFIA may map spectroscopic features in the disk as well, for example the water ice feature at 48 microns and the polycyclic aromatic hydrocarbon (PAH) features at 5.2, 6.2 and 7.7 microns. Such features help to ascertain the composition of the dust and hence the nature of planets which may be forming at particular locations in the disk. High spectral resolution observations of molecular gas in the disk may also provide insights into dynamics of disk evolution.

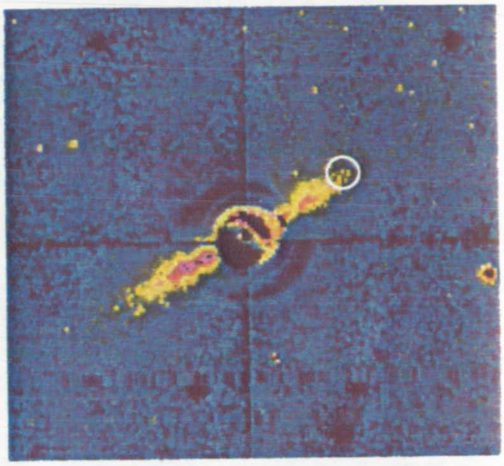

Figure 4. Optical photograph of the β Pic disk, with 60 μm SOFIA beam size superposed. The stellar image has been blocked with an occulter.

(v) Our Solar System:

The initial composition of our pre-solar nebula is of great interest because it contained the building blocks of the planets and of life. SOFIA's ability to explore an early pre-planetary system environment through observations of nearby circumstellar disks was discussed in § (iv). SOFIA will also map, spectroscopically as well as photometrically, dense clumps in nearby dark clouds, in order to determine the composition of future pre-solar nebulae. In order to study the origin of our Solar System more directly, a study of comets is essential since they are the most likely bodies to have preserved information about the pre-solar nebula. The remarkable discovery of water vapor in Comet Halley from the KAO clearly demonstrated the value of airborne observations of comets. Even though the discovery of organic material in the nuclear dust of Comet Halley was achieved from the ground looking at the C-H stretch feature near 3 microns, in order to determine the nature of the molecules producing this feature we must observe these species between 5 and 8 microns where the C–O, C–C, and C–N stretch bands are found. These wavelengths cannot be observed from the ground, but are readily accessible to an airborne platform. SOFIA will have the sensitivity, which in most cases is lacking on the KAO, to study a number of short period comets, observing their solid-state spectral features (such as olivine and water ice) as well as their gaseous features (e.g. CO_2). These comets have orbits that extend to about 7 AU from the Sun, and therefore may contain material that has undergone considerable processing by solar radiation. Comparison of these materials with those seen in long period comets, which sample a more pristine environment, will be extremely interesting.

A related fundamental question concerns the initial compositions of the volatiles incorporated into the giant planets and their satellites during formation, since these would imply certain conditions in the regions of the solar nebula where they formed. Two extreme models are that the outer planets and their satellites consisted of (a) water, methane, and ammonia (in order of decreasing abundance) or (b) carbon monoxide, water, and molecular nitrogen. In the currently accepted model, the giant planets consisted of composition (b), while in their satellites composition (a) dominated. Jupiter and Saturn might have converted the carbon monoxide to carbon dioxide and methane, and the nitrogen to ammonia, but Uranus and Neptune should have retained substantial amounts of their original composition. The satellites of the outer planets might retain surface spectral signatures of the primordial partitioning of these constituents. The atmospheres of these bodies are still very poorly known because of the many observational complications. One complication is the obscuration by the Earth's atmosphere of important planetary CO_2, CO, H_2O, H_2S, HD, and other molecular lines. Another difficulty is that the planets have spatial structure: there is interference from their rings, and their satellites have close orbits. The improved spectral and spatial resolution of SOFIA will enable measurements of these obscured molecular lines, since the spatial resolution will minimize rotational broadening. Where residual absorption in the low stratosphere is a problem, SOFIA's high spectral resolution will often separate telluric features from the planetary lines by Doppler shifts between Earth and the object observed. The spatial resolution of SOFIA will often allow separation of the far-infrared emission from an outer planet and its ring system or satellites. At the distance of Saturn, for example, the ball of this giant planet subtends roughly 15 arcseconds, whereas SOFIA's beam at 100 μm is about 8 arcseconds, and decreases to a few arcseconds in the near-infrared. A number of photometric and spectroscopic studies of a planet's rings and nearby moons can be carried out without contamination from the planet's emission.

Stellar occultations give us another method for exploring the outer solar system. This technique allows us to probe atmospheres and rings with a spatial resolution of only a few kilometers. An airborne observatory is particularly valuable for occultations, since it permits the telescope to be optimally located for a particular occultation event. The value of deployment has been demonstrated by the KAO's history of occultation work, most dramatically by the discovery of the unique ring system around Uranus in 1977 (Fig. 5). SOFIA will be capable of observing many more occultations than the KAO, with greatly improved signal-to-noise, because of its increased aperture and improved image quality. Occultations will be observed from SOFIA for several different studies. One such study would be to obtain temperature, pressure, and number density profiles of the atmospheres of Triton and Pluto, bodies for which no spacecraft entry probes are currently planned. SOFIA can also be used, in conjunction with HST observations, to vastly improve our knowledge of Saturn's ring dynamics through observations of a series of ring occultations. From observations spanning several years, the orbits of the edges and narrow singlets in the ring system can be determined with much greater precision than has been possible with flyby spacecraft. Improved orbital information will lead to further understanding of the ages of the rings (whether they were formed with Saturn or more recently), the evolutionary processes in particle disks, and the internal structure of Saturn (from its gravitational harmonic coefficients).

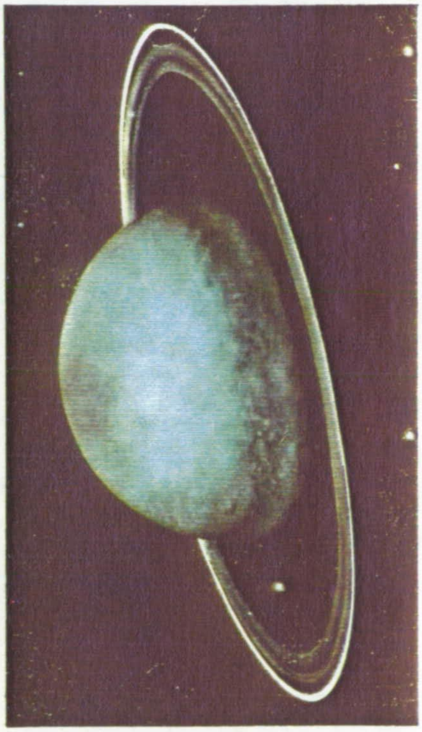

Figure 5. Artist's concept of the rings of Uranus discovered from the KAO.

(vi) The Sun:

The star that influences Earth the most is our Sun, not only through its radiation but through its solar wind as well. The solar wind originates in the chromosphere and corona, although the energy transport mechanism which heats the corona and drives the wind is not well understood. Oscillation of the solar atmosphere probably plays a role in this process, and pioneering far-infrared observations on the KAO, combined with ground-based sub-millimeter observations, have detected the oscillations at different depths in the solar atmosphere. Wavelength-dependent phase differences show the vertical transport of energy at the oscillation frequency. Far-infrared beam sizes from SOFIA will be well matched to the size of the oscillation cells, and provide improved information on the strength of the oscillations and on the correlation between adjacent cells. This will yield significant insight into the energy transport mechanisms in the solar atmosphere.

(vii) Reprocessing of the ISM:

The bulk of the elements heavier than helium have been synthesized in dying stars. These stars have finished the hydrogen burning phase in their cores and have commenced burning helium to form heavier elements. The central material is then mixed to the surface and is observable in the infrared in the form of bands of molecules, such as CN and CO, in the stellar spectrum. As the star evolves, these surface elements can be ejected back into the ISM by stellar winds, as in the case of the red giants, or in some cases by the loss of the star's whole outer shell, either at a non-catastrophic rate, as in the case of a planetary nebula, or at an explosive rate, as in the case of a supernova. In supernovae considerable nuclear synthesis can be achieved in the actual explosion; for example observations from the KAO detected lines from nickel, cobalt, and iron atoms produced by the explosion of Supernova 1987A. SOFIA's sensitivity and resolution would permit improved studies of bright supernova in other galaxies. Also, SOFIA will be well suited to study the common mass-loss stars such as the red giants and planetary nebulae, with sufficient sensitivity to permit resolution of the spectral lines of many important atoms and molecules, permitting studies of both the dynamics and rates of mass-loss.

(viii) Other Galaxies:

Observations from the KAO discovered that spiral galaxies typically emit as much energy at far-infrared wavelengths as they do throughout the visible and ultraviolet. The extensive IRAS observations of galaxies showed that many have infrared luminosities exceeding their visible luminosities by factors of ten or more. Thus it is clear that much important information on galaxies is available only through infrared observation, which SOFIA will enormously facilitate.

Various current theories predict distinct forms for the large-scale patterns of star formation and evolution of elemental abundances over a galaxy and have profoundly different consequences for galaxy formation and evolution. The increase in sensitivity on SOFIA will allow numerous galaxies to be studied spectroscopically in the far-infrared for the first time. For the closer galaxies, SOFIA will have sufficient spatial resolution to single out regions of active star formation and study some of the large structure dynamics (based on line profiles) in various types of galaxies. These data will provide unique evidence regarding the distribution of stellar types, the morphology of the ionized gas, and its relation to the distribution of the dust and luminous stars. For example, KAO measurements of O III (52 and 88 μm), N III (57 μm), O I (63 μm) and Si II (35 μm) line profiles from the obscured nucleus of the starburst galaxy M82 are consistently asymmetric and suggest strong variation in the emission from different components of the source. These components may be areas of intensive localized star formation, or recent supernova outbursts; supernovae are thought to occur in M82 *every few years*. Judging from radio maps, SOFIA could readily isolate

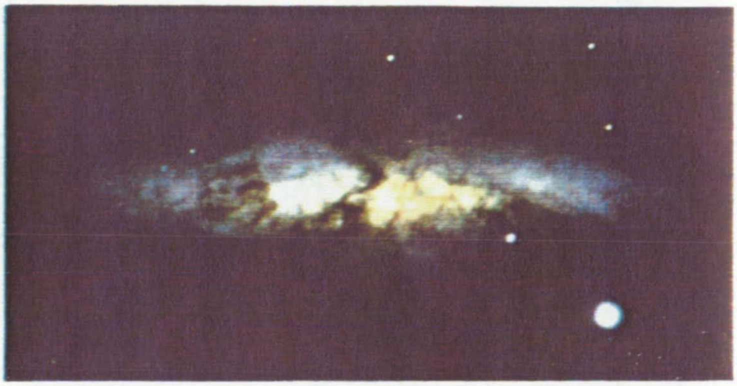

Figure 6. Optical photograph of M82.

some of the candidate components, but the KAO cannot. The disturbed visible appearance of M82 (Fig. 6) gives only a hint of the recent formation and violent demise of massive stars there.

Many of the galaxies found to have large infrared excesses by IRAS have subsequently been identified as galaxies in collision. Study of these ultraluminous infrared mergers is seriously hindered at near-infrared, optical, and ultraviolet wavelengths because of the large obscuration by dust embedded in them. However, SOFIA will permit photometric imaging on a scale of 8 arcseconds at 100 μm, easily adequate to reveal brightness distributions of emitting dust on a scale comparable to the visible structure seen in many of these systems, and ample to distinguish the individual components.

Figure 7 shows the interacting galaxy pair NGC 7318 in Stephan's Quintet. The image is a superposition of two optical CCD images taken through two filters. The red coloration is produced by the older generation of stars that make up the bulk of the galaxies, while blue-green coloration shows the distribution of ionized hydrogen gas, which traces sites of recent star formation activity within the galaxies. The nuclei of the two galaxies are separated by 20 arcseconds.

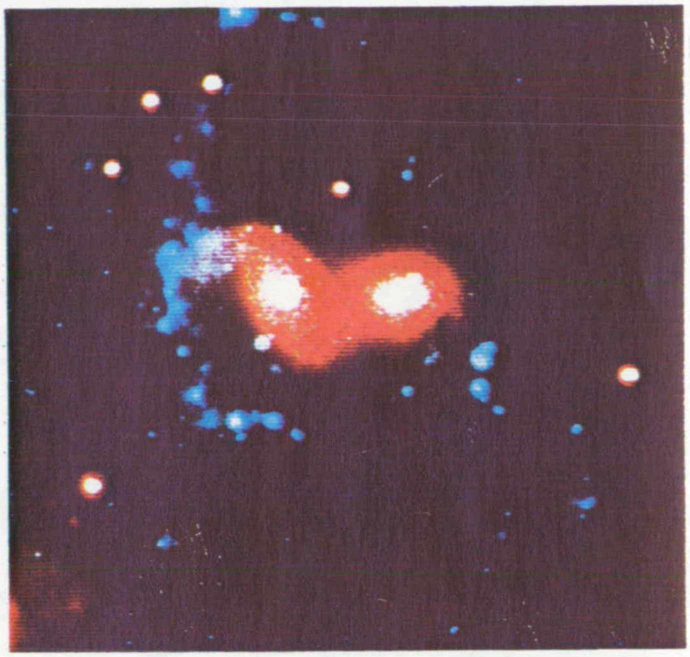

Figure 7. CCD image of the galaxy pair NGC 7318.

Maps at different wavelengths, including those beyond 100 μm which IRAS did not sample, will yield temperature and optical depth profiles. Far-infrared and submillimeter spectroscopy will probe the excitation conditions, temperature, density, composition, and dynamics of the gas in these systems with similar spatial resolution. Rotational CO lines, and fine structure lines of O I, Si II, C II, O III, S III, and N III, will be important diagnostics. Together these techniques will help to distinguish between massive bursts of star formation or obscured central objects as the central engines in these infrared-luminous mergers.

(ix) The Galactic Center:

In many ways, the most exciting place in our own Galaxy is at its center. It has an infrared luminosity of roughly 10^7 $L_\odot$, is enshrouded in a dense dust ring, and is obscured at visible wavelengths by the intervening dust in the galactic plane by a factor of roughly 10^{10}. The distribution of red stars can be studied (with large extinction corrections) in the near-infrared and the distribution of ionized gas can be studied at radio wavelengths. However, the distributions of neutral atomic gas, thermally emitting dust, and ionized-gas cooling can best be studied at the wavelengths accessible to SOFIA. A ring of dust emission about the galactic center – which was first discovered from the KAO – is about 3 arcminutes in diameter and the cavity it defines at the center is only 30 arcseconds in diameter. The results achieved so far show that material from the ring may be spiralling into the center, that high turbulent velocities are present, and that magnetic fields may be very important in this region. The data are consistent with the existence of a massive central object, possibly a black hole. SOFIA will clarify this picture on a finer spatial scale by resolving regions of different velocities, magnetic field directions (i.e. polarizations), temperatures, and densities, obtaining a more accurate measure of the total luminosity of the central powerhouse which is illuminating the surrounding material. SOFIA will thus provide fundamental data bearing on our own galactic center, which in turn will be a crucial step toward understanding similar phenomena seen on larger scales in many other galaxies.

B. GENERALITY OF INTEREST

1. WHY IS SOFIA IMPORTANT OR CRITICAL TO THE PROPOSING SCIENCE DISCIPLINE (ASTRONOMY AND ASTROPHYSICS)?

The primary goal of astronomy and astrophysics is to trace and understand the history of the Universe and to predict its future. Most of the energy emitted in the Universe appears longward of 1 μm and it is therefore not surprising that many of the major contemporary goals of astronomy and astrophysics involve the study of phenomena whose primary radiation output is in the infrared, far-infrared, and sub-millimeter. These include: (i) probing the earliest stages of the Universe to learn how galaxies form and evolve to their current state; (ii) learning more about cosmic energy sources, including active galaxies and quasars; (iii) studying the formation of stars and their subsequent evolution; and (iv) understanding the formation of planets and of the solar system, including the conditions necessary for life to form and evolve in the Universe.

SOFIA will be critical for the understanding of the issues in (iii) and (iv), since these issues involve the "local Universe," where breakthroughs in knowledge will be made through an increase in spatial and spectral resolution as well as sensitivity. Much of the work in (i) and (ii) involves the "distant Universe," where a dramatic increase in the broadband sensitivity is required before we can expect a significant increase in our understanding of many of the issues involved. Here SIRTF will be absolutely critical.

However, there are some aspects of the early Universe that can be studied by observing the local Universe using SOFIA's superior spectral and spatial resolution. For example, SOFIA will contribute significantly to item (ii) by permitting unique observations of the brighter of the highly luminous infrared galaxies found by IRAS. SOFIA may also permit discovery of the molecule HD produced in red carbon stars, which would have a major impact on the determination of the amount of deuterium produced in the Big Bang and hence the character of our Universe at birth.

2. WHAT IMPACT WILL THE SCIENCE ACCOMPLISHED BY SOFIA HAVE ON OTHER DISCIPLINES?

As discussed in §A, SOFIA will have a large impact on planetary science, particularly by providing new insights into the evolution of our own Solar System by exploring the pre-solar and solar nebulae of other systems. Studies of comets and the outer planets will give us specific information relevant to the primitive solar nebula.

SOFIA will also be important in areas of chemistry and space life science, since the Interstellar Medium is a very low density environment, one which cannot be reproduced on Earth. Low density, low temperature chemical processes can be studied with SOFIA. For example, the products of the most elementary chemical reactions in space are the hydrides, which in many cases cannot be observed from the ground. SOFIA will be able to determine their relative abundances from fundamental rotation transitions at sub-millimeter wavelengths. Also, in the last few years, strong evidence has been obtained via infrared spectroscopy and photometry, that a rich and complex organic chemistry exists in the ISM (e.g. the discovery from the KAO of polycyclic aromatic hydrocarbons, or PAH's). With SOFIA it will be possible to trace out the distribution of this organic material and perhaps learn more about the conditions in space that contribute to the formation and survival of these species.

SOFIA will be relevant to nuclear physics, since there are large uncertainties in some nuclear reactions that occur in red giants. The relative abundances of the products of these reactions can be observed via their molecular rotational and vibrational transitions using SOFIA, since the core material is mixed to the surface of these stars. We can also hope to understand the forms in which the building blocks of life were carried into our Solar System.

3. IS THERE A POTENTIAL FOR CLOSING A MAJOR GAP IN KNOWLEDGE, EITHER WITH AN IMPORTANT DISCIPLINE OR IN AREAS BRIDGING DISCIPLINES?

SOFIA has the potential to help us finally understand how a large cloud can fragment and form stars out of those fragments, and then in some cases proceed to form planetary systems. There exists no quantitative, non-spherically symmetric theory of this complete process, partly because such a theory extending from interstellar to stellar dimensions involves a very large dynamical range, one that cannot be handled by modern computers. Thus nonspherical star formation theory must be divided into tractable stages. The successive stages must have consistent boundary and initial conditions. Observations from SOFIA can provide important constraints for these semi-empirical models, leading to a much deeper understanding of this fundamental problem.

C. POTENTIAL FOR NEW DISCOVERIES AND UNDERSTANDING

1. DOES SOFIA PROVIDE POWERFUL NEW TECHNIQUES FOR PROBING NATURE? WHAT ADVANCES CAN BE EXPECTED BEYOND PREVIOUS MEASUREMENTS, WITH RESPECT TO ACCURACY, SENSITIVITY, COMPREHENSIVENESS, AND SPECTRAL DYNAMIC RANGE?

SOFIA will provide a powerful new facility for probing the Universe. The ongoing state-of-the-art instrument development possible on such an observatory will ensure that the facility will work to its maximum potential. SOFIA will cover the same wide spectral range as does the KAO – from 0.3 µm to 1.6 mm. However, SOFIA will be roughly 10 times more sensitive for compact sources and it will have three times the spatial resolution of the KAO because of its bigger primary mirror. Hence, SOFIA will be able to carry out observations in a volume of space nearly 40 times larger than is currently available and study structures that are 3 times smaller. The spectrometers that will fly on SOFIA will be able to take advantage of this increase in sensitivity to increase their spectral resolving powers where needed. Recent development of heterodyne techniques stimulated by the availability of the KAO has produced spectrometers with resolving powers of 10^6 down to wavelengths as short at 118 µm. It is expected that heterodyne spectrometers will be used on SOFIA down into the 10-100 µm range. Recently large format, areal array cameras have been developed in the near-infrared and are being used at large ground-based observatories. These arrays make it possible to map out large regions and study large scale structures such as shocks and cloud heating. Similar arrays (although much smaller) are being developed on the KAO for the far-infrared and sub-millimeter. SOFIA will encourage more work in this area because it offers smaller diffraction-limited beam sizes and higher sensitivity.

SOFIA, with its 2.5 meter telescope, will be able to observe any of the IRAS compact sources. Future cryogenically cooled space observatories, such as SIRTF and ISO, will have much higher broad-band sensitivities than SOFIA. They will primarily be interested in the early and distant Universe, in questions of cosmology, and in the fainter objects in the local Universe. SOFIA, on the other hand, will concentrate on the brighter phenomena in the local Universe where the issues require the higher spectral and spatial resolving power of the airborne observatory.

Nonetheless, SOFIA will undoubtedly be called upon many times to carry out follow-up observations of SIRTF discoveries.

2. IS THERE A POTENTIAL FOR REVEALING PREVIOUSLY UNKNOWN PHENOMENA, PROCESSES, OR INTERACTIONS?

There are so many gaps of understanding in the theories of stars and planet formation, galaxy evolution, and the origin of life that every new piece of data on these topics is likely to reveal previously unknown phenomena, processes, or interactions. These are areas of research where theory is very closely coupled to observations, since (as stated in §B.3) the dynamical ranges of these problems are so large that theorists must be guided by observations in order to divide the problems into tractable stages. For example, the powerful bipolar outflows observed recently in many young stellar objects were a complete theoretical surprise, and were observed only because of an increase in spatial and spectral resolution in the millimeter observations of the CO rotational lines. The bipolar outflows are not only a surprise: they are still a complete mystery. There is no theory available to explain how young stars can be so efficient at generating and directing such outflows. The process which drives the outflows may well be an entirely new one. Similar discoveries certainly await far-infrared astronomers as they start to probe the local Universe with higher spatial and spectral resolution.

3. IN WHAT WAYS WILL SOFIA ANSWER FUNDAMENTAL QUESTIONS OR STIMULATE THEORETICAL UNDERSTANDING OF FUNDAMENTAL STRUCTURES OR PROCESSES RELATED TO THE ORIGIN AND EVOLUTION OF THE UNIVERSE, THE SOLAR SYSTEM, THE PLANET EARTH, OR OF LIFE ON EARTH?

As discussed in §A, SOFIA's prime objective is to improve our understanding of the origins and evolution of stars, the Solar System, Earth and life. The origin and early evolution of the Universe is really in the realm of a space telescope such as SIRTF, because of the sensitivity required. However, SOFIA will be important in the study of the evolution of galaxies in the local Universe, since it will be able to study and locate the star formation regions of galaxies, the different chemical abundances in galaxies, the effects of galaxy collisions and tidal forces in galaxy clusters, and the activity at the center of some galaxies, especially our own. SOFIA's comprehensive complement of spectrometers will allow detailed study of the organic chemistry in the ISM, the origin and evolution of the biogenic elements, and the conditions existing in preplanetary nebulae which all bear on the questions surrounding the origin of life.

4. IN WHAT WAYS WILL SOFIA ADVANCE UNDERSTANDING OF IMPORTANT AND WIDELY-OCCURRING NATURAL PROCESSES AND STIMULATE MODELING AND THEORETICAL DESCRIPTION OF THESE PROCESSES?

As discussed in §A.3, SOFIA's prime purpose is not to study the exotic phenomena of the Universe but the common, widely-occurring natural processes, which are very poorly understood. One look at our Universe, for example, will reveal that star formation is indeed very common, since most of the matter in a galaxy is in the form of stars. The overall mass budget of a galaxy (i.e. the star formation rate versus the mass loss rate of dying stars) and its metalicity are quantities of great interest, because they determine how a galaxy will change with time. Observations from SOFIA of the composition of the ISM, the star formation rate, and the rate at which processed material is returned to the ISM for our Galaxy and other galaxies will give us enhanced insight into this overall issue and will provide critical data for testing models and theories of stellar and galactic evolution.

5. IS THERE A POTENTIAL FOR DISCOVERING NEW LAWS OF SCIENCE, NEW INTERPRETATIONS OF LAWS, OR NEW THEORIES CONCERNING FUNDAMENTAL PROCESSES?

Although SOFIA's prime purpose is not the study of exotic phenomena, these phenomena are not entirely excluded. Indeed SOFIA will be used extensively to study the center of our Galaxy where there may well be lurking a black hole. Such a phenomenon is considered a singularity in the mathematical framework of the Universe. It is at such singularities that our laws of physics are put to the test, just as they are near the speed of light and at the beginning of the Universe, the Big Bang.

D. UNIQUENESS

1. WHAT ARE THE SPECIAL REASONS FOR PROPOSING THIS INVESTIGATION AS AN AIRBORNE MISSION? ARE THERE OTHER WAYS THAT THE DESIRED KNOWLEDGE COULD BE OBTAINED?

Infrared data are essential for understanding many diverse phenomena in the Universe. Our understanding of our surroundings will be essentially incomplete without such work. For example, even the most basic quantities such as total luminosity, temperature, and mass of an obscured young stellar object could not be determined without far-infrared observations, which are unattainable from the Earth's surface. Hence, an observatory which operates in or above the stratosphere is essential. The KAO has served and strengthened the infrared community well over the past 15 years; however, it has brought us to a stage where many important questions are just out of reach. These were listed in §A.3. Although a spaceborne mission could do the science planned for SOFIA, it would be considerably more expensive and could not readily provide the variety of state-of-the-art instrumentation which will be developed and promptly applied over SOFIA's extended operating lifetime. To put the project in perspective, one has only to remember that the 0.9 meter KAO telescope is the sole observatory-class facility routinely available for most of the infrared spectral range. Imagine what the demand for a larger ground-based telescope would be if the *only one* in existence had a 0.9 meter aperture!

2. IS THERE A SPECIAL REQUIREMENT FOR LAUNCHING SOFIA ON A PARTICULAR TIME SCHEDULE?

SOFIA should be "launched" as soon as possible, i.e., in the late 1990's, to provide supporting observations for the infrared instrument (NICMOS) on HST, and for SIRTF. SOFIA's 20 year lifetime will ensure that it will still be available well beyond the SIRTF era. A progressive airborne astronomy program is needed now because it is a major factor in the development of scientific background, observing techniques, instrumentation, and personnel in the discipline of infrared astronomy. SOFIA would bridge the gaps between IRAS, SIRTF, and LDR in all four of these vital areas.

II. PROGRAMMATIC CONSIDERATIONS

OVERVIEW

Astronomers have been using aircraft to obtain astronomical data which are inaccessible to ground-based observers for a quarter of a century. The pioneering airborne astronomy program sponsored by NASA has been a major factor – through science, technology, and education – in establishing U.S. leadership in infrared astronomy. Fundamental results have been obtained starting in the 1960's from NASA's Convair 990, U-2, Learjet, and the C-141 Kuiper Airborne Observatory; these extend in wavelength from the near ultraviolet, through the visible, infrared, and sub-millimeter parts of the spectrum, and include studies of the Sun, the planets and satellites, the Galaxy, extragalactic objects, and the 3 K cosmic background. Major technological advances in detector, telescope, and focal plane instrument design have been stimulated by the opportunities for airborne observations. Numerous scientists currently involved in spaceborne and ground-based projects have benefited significantly from their airborne experience. As successor to the KAO, SOFIA will continue this tradition of excellence with greatly enhanced capabilities, supporting and complementing space astronomy missions into the second decade of the next century.

NASA's partner in SOFIA, the German Space Agency (DARA), will contribute the telescope assembly to the development, and part of the operating costs. In return, German scientists will be assured a fraction of the observing time and the benefit of experience which will be valuable in future projects.

A. FEASIBILITY AND READINESS

1. IS SOFIA TECHNOLOGICALLY FEASIBLE?

The SOFIA design relies heavily on the successful technology of the KAO, which has demonstrated excellent stability for an open-port telescope operating at high altitude in a modern jet transport. Concept and definition studies carried out in the U.S. and Germany in 1986-1989 show that the major scientific requirements can be satisfied with reasonable extrapolations of existing technology.

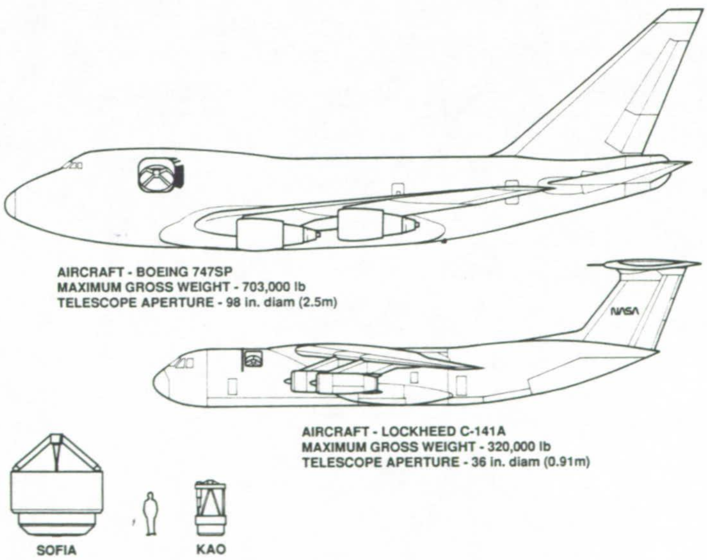

Figure 8. SOFIA and KAO

Figure 8 shows the concept for SOFIA: a 2.5 meter, open-port telescope in a Boeing 747 airplane, providing continuous in-flight access to focal plane instruments. The unique characteristics of the Boeing 747, i.e., a wide body with forward bulge and 4 engines, make it the *only* aircraft with the performance and capacity required for a telescope of this size. The figure also compares the aircraft and telescopes for SOFIA and the KAO. The SOFIA telescope is much larger relative to the Boeing 747 than is the KAO telescope relative to the Lockheed C-141. This means that the SOFIA telescope design must be more sophisticated than the KAO: the SOFIA primary mirror must be roughly f/1.2 to prevent large obscuration by the secondary, and must be lightweight to minimize the telescope mass. Also, whereas the KAO uses a "fence" ahead of the telescope cavity to deflect the airflow, SOFIA is shown with an "aft ramp" which has less drag and is thought to improve the seeing degradation caused by the shear layer streaming over the cavity.

Figure 9 depicts the telescope design which evolved during the conceptual and definition studies. A pneumatic isolation system carries the telescope on the rear of two full pressure bulkheads which bound the unpressurized telescope cavity. A diaphragm arrangement balances the pressure differential across the bulkhead. The isolators support an air-bearing stator, whose rotor is rigidly attached to the telescope assembly via a stiff connecting tube. Gyroscopes provide high frequency stabilization and a video star tracker provides the low frequency stability. This configuration is similar to that of the KAO. Its principal advantages are the low friction of the air bearing – allowing sub-arcsecond pointing – and continuous in-flight access to the focal plane instruments by scientists in a shirtsleeve environment.

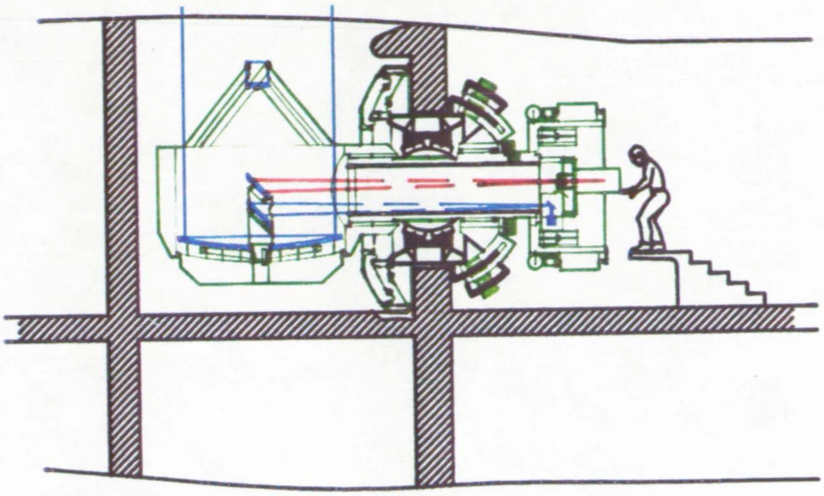
Figure 9. SOFIA Telescope Concept

A dichroic tertiary mirror deflects the infrared beam to the instrument focal plane located just aft of the air bearing. The visible beam is reflected to a focal plane camera near the infrared focal plane. This arrangement minimizes the background emission seen by the infrared instrument, permitting the visible camera to stabilize the image while compensating for small deformations of the telescope structure. The snub nose at the upper right is the "aft ramp" shear layer control mentioned above. It is clear from system concept studies that the aircraft modification, the telescope, and the integrated observatory are technically feasible.

2. ARE NEW TECHNOLOGICAL DEVELOPMENTS REQUIRED FOR THE SUCCESS OF SOFIA?

The fabrication and support of a fast, lightweight, thermally stable, 2.5 meter primary mirror will be challenging, because such a mirror has never been made. Nevertheless, both American and German mirror manufacturers agree this is possible. Detailed analysis of a prototype telescope structure showed that deformations were small enough to maintain the 1.5 arcsecond visible image quality requested by the scientists.

An air bearing as large as that needed to support the telescope has also never been built. It provides very low friction and a pressure seal between the cabin and the cavity. Again, several potential suppliers concur that this is a feasible concept.

Boeing Military Airplanes Company studied the aircraft modification. Only the shear layer control system, which manages the airflow over the cavity, was a concern which required further study to select the optimum practical solution. Although a new control system may be adopted, the "fence" system used on the KAO is workable.

Thus, instead of new technological developments, SOFIA will require innovative engineering to achieve the requested performance.

3. ARE THERE ADEQUATE PLANS AND FACILITIES TO RECEIVE, PROCESS, AND ANALYZE THE DATA?

As with the KAO, data acquired on SOFIA will be taken by the investigators to their home institutions for processing and analysis, and subsequent publication in the literature. No significant central facility is required.

4. IS THERE AN ADEQUATE MANAGEMENT AND ADMINISTRATIVE STRUCTURE TO DEVELOP AND OPERATE SOFIA?

Management and administrative structure to develop and operate SOFIA is planned at the NASA Ames Research Center, and, for the German participation, by the German Space Agency (DARA). Ames Research Center developed the Kuiper Airborne Observatory, and has operated it successfully since 1975, so the management and administrative structure is basically in hand.

B. SPACE OPERATIONS AND INFRASTRUCTURE

1. WHAT ARE THE LONG-TERM REQUIREMENTS FOR SPACE OPERATIONS, INCLUDING LAUNCHES, REPLACEMENT AND MAINTENANCE OF INSTRUMENTS, AND DATA RELAYS?

For SOFIA there are no space operations. The facility is its own launch vehicle. Instruments will be frequently upgraded by the investigator teams who provide them, as is the case on the KAO. No data relays are needed.

2. WHAT CURRENT AND LONG-TERM INFRASTRUCTURE IS REQUIRED TO SUPPORT THE MISSION AND THE ASSOCIATED DATA PROCESSING ANALYSIS?

The current infrastructure for the KAO operations includes ground crew, flight crew, telescope operators, mission directors, and support personnel. This staff will be expanded to accommodate an enhanced flight rate on SOFIA. A small staff of computer programmers, who support the operation of SOFIA, will also be available for consultation with investigators regarding data acquisition and processing.

C. COMMUNITY COMMITMENT AND READINESS

1. IS THERE A COMMUNITY OF OUTSTANDING SCIENTISTS COMMITTED TO THE SUCCESS OF SOFIA?

Over 300 scientists have flown on the KAO. This group contains Nobel laureates, members of the National Academy of Science, and other widely recognized members of the astronomical community. Observing is heavily oversubscribed. There is no doubt that SOFIA, with this heritage, has very broad-based support.

The study activities have been guided over the past several years by the SOFIA Science Working Group which is listed below. Most, but not all of these are regularly principal investigators on the KAO. A number of other scientists have contributed on an ad hoc basis to the studies and technical reviews, as suited their competence and interests.

SOFIA SCIENCE WORKING GROUP

MEMBERS:

A. L. Betz, UCB
L. J. Caroff, NASA HQ
J. A. Davidson, SETI
E. W. Dunham, NASA Ames
E. F. Erickson*, NASA Ames
R. Genzel, MPIEP
D. A. Harper, Yerkes
P. M. Harvey, U. Texas
T. L. Herter, Cornell
D. J. Hollenbach, NASA Ames
H. P. Larson, U. Arizona
D. F. Lester, U. Texas
H. A. Moseley, NASA GSFC
H. P. Roeser, MPIfR
H. A. Thronson, U. Wyoming
J. Stutzki, U. Cologne

ex officio

W. Brunk, NASA HQ
R. J. Pernic, Yerkes
A. Meyer, KAO

* Chairman, Project Scientist

2. IN WHAT WAYS WILL THE COMMUNITY PARTICIPATE IN THE OPERATION OF SOFIA AND THE ANALYSIS OF THE RESULTS?

SOFIA will be operated by NASA, with guidance provided by the approved investigators in the form of a SOFIA users' group, following the successful model set by the KAO users' group. Annual and/or bi-annual peer review of observing proposals is anticipated. The peer review panel, which is selected from the astronomical community at large, will also be given the opportunity to make recommendations regarding the operation of the facility. It can also be anticipated, based on the KAO operation, that instrument-oriented investigators will contribute significantly to upgrades of the facility over its lifetime, as new technology becomes available. As described in §B.2 above, investigators will analyze their data at their home institutions.

D. INSTITUTIONAL IMPLICATIONS

1. IN WHAT WAYS WILL SOFIA STIMULATE RESEARCH AND EDUCATION?

The opportunities for observations with SOFIA will attract not only observers with ideas which exploit its unique scientific capabilities, but also instrumentation physicists and engineers who recognize the potential for application of state-of-the-art technologies in new focal plane instruments.

The possibility of hands-on participation in research on SOFIA will be extremely attractive to graduate students and young scientists. This attraction arises not only from the uniqueness of the research and its importance to astronomy, but also from the small scale on which it can be carried out. Individual professors with one or two graduate students can effectively carry out a research program. Students can be involved in all aspects of the research: conception of ideas, instrumentation development and operation, observation planning, data acquisition, processing, analysis and interpretation, and publication. Following the tradition of the airborne program, which has provided dissertation topics for over 40 Ph.D.'s, SOFIA will offer exciting research opportunities to many young scientists.

2. WHAT OPPORTUNITIES AND CHALLENGES WILL SOFIA PRESENT FOR THE CENTERS, CONTRACTORS, AND UNIVERSITIES?

Only Ames Research Center within NASA will be involved significantly in the development and operation of SOFIA. This will be a challenging task, especially in the development stage, because of the desire to optimize the performance of the observatory for operation over such a wide wavelength range and for such a diverse community. This will be a major opportunity for NASA, however, because much of the experience gained will be applicable to future space projects such as SIRTF and especially LDR. The development of the aircraft system will be done by a competitively selected U.S. contractor. The development of the telescope assembly will be done by a competitively selected German contractor. The university community will participate in an advisory capacity on the project, will develop most of the focal plane instruments, and ultimately will carry out the majority of the observations.

3. WHAT WILL BE THE IMPACT OF SOFIA ON OSSA ACTIVITIES?
WILL NEW ELEMENTS BE REQUIRED?
CAN SOME CURRENT ACTIVITIES BE CURTAILED IF SOFIA IS SUCCESSFUL?

At the proposed minimum flight rate of 120 research missions per year, SOFIA will require an augmentation to the operating budget currently required for the KAO. In the future, higher flight rates can be realized with the SOFIA. *No additional OSSA organizational elements will be required.* The KAO will be phased out of service about a year before SOFIA becomes operational.

E. INTERNATIONAL INVOLVEMENT:

1. DOES SOFIA PROVIDE ATTRACTIVE OPPORTUNITIES FOR INVOLVING LEADING SCIENTISTS OR SCIENTIFIC TEAMS FROM OTHER COUNTRIES?

By collaborative agreement, science teams from Germany would be guaranteed a fraction of the observing time on SOFIA. Teams from other countries could compete for time with U.S. proposers on the same basis that they have for time on the KAO, where successful foreign proposals have typically demonstrated capabilities or ideas not proposed by the U.S. community.

2. ARE THERE COMMITMENTS FOR SUPPORT FROM OTHER NATIONS OR INTERNATIONAL ORGANIZATIONS?

Germany has agreed to provide a major contribution to the development as well as operating costs commensurate with the fraction of flight time their science community would receive, roughly 20%. This agreement would be formalized prior to proceeding with development of the facility.

F. COSTS OF THE PROPOSED SOFIA FACILITY

Section IIF has been intentionally deleted.

III. SOCIETAL AND OTHER IMPLICATIONS

A. CONTRIBUTIONS OF SOFIA TO SCIENTIFIC AWARENESS AND THE IMPROVEMENT OF THE HUMAN CONDITION

1. ARE THE GOALS OF SOFIA RELATED TO BROADER PUBLIC POLICY OBJECTIVES SUCH AS HUMAN WELFARE, ECONOMIC GROWTH, OR NATIONAL SECURITY?

No direct contribution by SOFIA to human welfare or economic growth on a significant scale is anticipated. In terms of the human spirit, the development of SOFIA is an inspiring endeavor. While large aircraft are commonplace and large telescopes not uncommon in our society, large airplanes with large telescopes do not exist; thus SOFIA will represent a combination of some of our most sophisticated technologies. Indeed, the concept of accurately pointing a large telescope in a moving airplane is counter-intuitive, and its realization will be a tribute to human ingenuity. Airborne astronomy itself and the results it produces rarely fail to stimulate and inspire the perceiving intellect. By giving man a readily accessible window through his atmospheric cocoon, airborne astronomy allows individuals to expand the limits of human perception. Thus by providing new knowledge about the Universe, and as an example of the potential for human achievement, SOFIA may affect human welfare and economic growth in intangible but positive ways.

In addition of course there may be unanticipated tangible benefits. SOFIA will stimulate technology that may find application in medicine, for example infrared imaging of tissues. Possibly SOFIA will elucidate new physical or chemical principles which could find practical application. Serendipitous discoveries have certainly occurred in other technical endeavors, and so would not be cause for surprise in the case of SOFIA. In terms of national security, several technologies required for SOFIA are significant. Among these are infrared detectors, fast optics, airborne optical pointing systems, aero-optical physics, and cryogenic systems.

2. WHAT IS THE POTENTIAL FOR STIMULATING TECHNOLOGICAL DEVELOPMENTS BEYOND SOFIA?

The tremendous observing potential, long lifetime, and frequent opportunities for participation which SOFIA will offer the scientific community assure the development and prompt application of new technologies on SOFIA. These will surely be valuable in future space and ground-based astronomy, as well as in other areas. Again, the history of the airborne astronomy program is a guide: the chopping secondary mirror, a feature of all modern infrared telescopes, was initially developed for the Learjet telescope. This facility also allowed the first "hands-on" testing of far-infrared bolometer detectors in an astronomical application. Detectors developed for use on the KAO were used on IRAS. Experience with KAO focal plane instruments has been applied to the design of IRAS, COBE, ISO, SIRTF, and AXAF focal planes.

Planned space projects which will benefit in a major way from SOFIA-related technology are NASA's Large Deployable Reflector (LDR) and ESA's Far-Infrared Space Telescope (FIRST). These are ambient temperature telescopes which will operate throughout the far-infrared and sub-millimeter parts of the spectrum, and for which SOFIA will be the main precursor.

3. HOW WILL SOFIA CONTRIBUTE TO PUBLIC UNDERSTANDING OF THE PHYSICAL WORLD AND APPRECIATION OF THE GOALS AND ACCOMPLISHMENTS OF SCIENCE?

The extensive participation in observing by the science community, and the opportunities for the media to experience science in action on SOFIA will ensure visibility and dissemination of the wide variety of scientific results anticipated. SOFIA's rapid response to ephemeral astronomical events also will contribute to its ability to attract and focus public attention on science.

B. CONTRIBUTION OF INTERNATIONAL UNDERSTANDING

1. WILL SOFIA CONTRIBUTE TO INTERNATIONAL COLLABORATION AND UNDERSTANDING?

The planned involvement of the German science community and industry in the development and operation of SOFIA will be a significant contribution. The fact that the observatory will be deployed abroad for a variety of investigations not possible from NASA/Ames will provide international visibility for the facility, its achievements, and its goals. For example, the KAO has operated successfully out of Japan, Australia, and New Zealand. SOFIA's unique capabilities will foster foreign collaborative activities, both on SOFIA and by U.S. investigators at foreign facilities. The need to have the broadest possible spectral coverage for the interpretation of the characteristics of a source, such as far-infrared airborne data and radio observations from the ground, are a strong stimulus for correlative observations which often involve international collaboration. Airborne investigations sponsored by NASA have already involved international collaborations, for example with Australian, French, Dutch, German, Italian and Swedish scientists.

2. DOES SOFIA HAVE ANY ASPECTS REQUIRING SPECIAL SENSITIVITY TO THE CONCERNS OF OTHER NATIONS?

As a unique astronomical facility, SOFIA will attract the interest of scientists from many nations. Its bi-national sponsorship will naturally enhance SOFIA's international visibility, thereby stimulating research ideas in the worldwide science community. Foreign scientists will be welcome to submit proposals for observations, as discussed in §II E.1 above. This situation will require tactful and diplomatic administration of the proposal review process, as has been the case throughout the duration of the airborne program.

C. CONTRIBUTIONS TO NATIONAL PRIDE AND PRESTIGE

1. HOW WILL SOFIA CONTRIBUTE TO NATIONAL PRIDE IN U.S. ACCOMPLISHMENTS AND THE IMAGE OF THE U.S. AS A SCIENTIFIC AND TECHNOLOGICAL LEADER?

2. WILL SOFIA CREATE PUBLIC PRIDE BECAUSE OF THE MAGNITUDE OF THE CHALLENGE, THE EXCITEMENT OF THE ENDEAVOR, OR THE NATURE OF THE RESULTS?

SOFIA *epitomizes* the American ideals of innovation, exploration, and achievement. Its aircraft platform already symbolizes the leadership of U.S. technology around the world. Its astronomical promise, moderate cost, and opportunities for broad-based community participation will continue the tradition of U.S. leadership in infrared astronomy. SOFIA's vision will penetrate dark reaches of our own and other galaxies, revealing objects and processes otherwise hidden from view with spatial resolution which will be unmatched until the next century. It will elucidate problems ranging from the spectacular death of massive stars to the inconspicuous incubation of low mass stars, from the composition of interstellar dust to the formation of prebiotic materials and protoplanetary systems, and from the enigmatic character of our own Galactic Center to the nature of stupendous luminosity sources in colliding galaxies. SOFIA's image, performance, and accomplishments will surely be a source of pride to all Americans who become acquainted with it.

UNITED STATES OF AMERICA

NASA DARA

SOFIA

STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY

FEDERAL REPUBLIC OF GERMANY

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6. AUTHOR(S)
E. F. Erickson, J. A. Davidson, G. Thorley, and L. J. Caroff*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ames Research Center
Moffett Field, CA 94035-1000

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Point of Contact: E. F. Erickson, Ames Research Center, MS 245-6, Moffett Field, CA 94035-1000
(415) 604-5508 or FTS 464-5508
*NASA Headquarters, Washington, DC

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13. ABSTRACT ***(Maximum 200 words)***

This document was originally prepared to describe SOFIA – the Stratospheric Observatory for Infrared Astronomy – for the Space and Earth Sciences Advisory Committee (SESAC) in May 1988. SESAC reported to Dr. Lennard Fisk, the NASA Associate Administrator who heads the Office of Space Science and Applications. The format and the questions answered in the report were provided by SESAC as a standard for judging the merit of potential U.S. space science projects. The report was updated in May 1990 for the Space Science and Applications Advisory Committee (SSAAC), which has superseded the SESAC. This version of the report was generated in June 1990 to intentionally delete Section IIF, which addressed development costs of the SOFIA Facility.

Several other projects are mentioned in the document by their acronyms. These are familiar to the space science community, but are given here (in approximate chronological order by mission commencement) for completeness. Only the KAO, IRAS, COBE and HST have flown.

Acronym	Name	Wavelengths
KAO	Kuiper Airborne Observatory	near UV, optical, IR, FIR, submm
IRAS	Infrared Astronomical Satellite	FIR
HST	Hubble Space Telescope	UV, optical
COBE	Cosmic Background Explorer	FIR, submm, mm
GRO	Gamma Ray Observatory	gamma rays
ISO*	Infrared Space Observatory	IR, FIR, submm
AXAF	Advanced X Ray Facility	X rays
SIRTF	Space Infrared Telescope Facility	IR, FIR, submm
FIRST*	Far-Infrared and Submillimeter Telescope	FIR, submm
LDR	Large Deployable Reflector	FIR, submm

Here UV refers to ultraviolet, IR to infrared, FIR to far-infrared, submm to sub-millimeter, and mm to millimeter. Roughly the IR corresponds to wavelengths from 1 to 10 microns (abbreviated μm), FIR from 10 to 100 μm, submm from 100 μm to 1 mm, and mm from 1 to 10 mm. The asterisks indicate projects being sponsored by the European Space Agency.

In the report we describe SOFIA's unique astronomical potential, and show how it complements and supports these existing and planned facilities.

14. SUBJECT TERMS
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