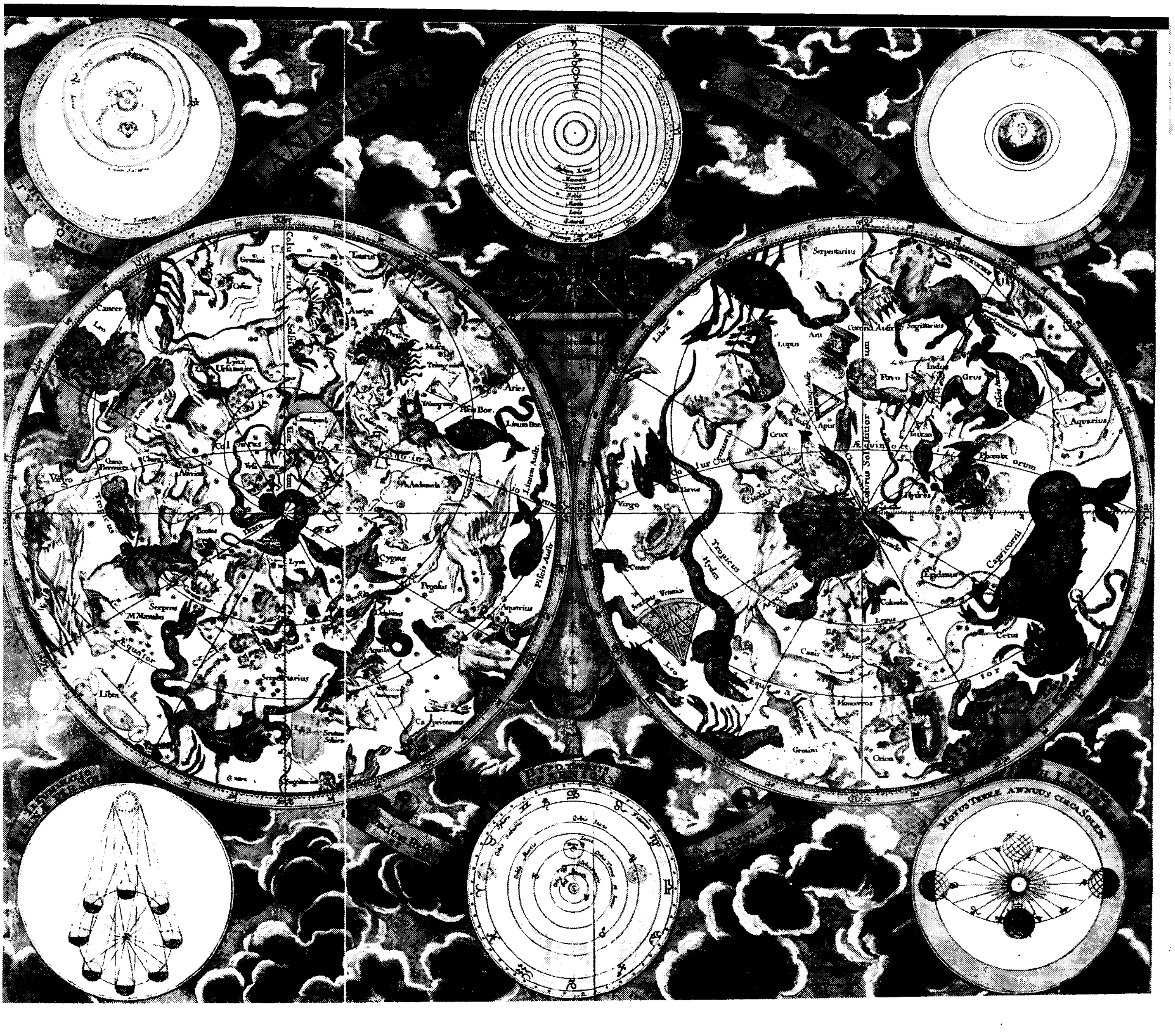
AN
INFRARED SPACE OBSERVATORY
(ISO)



A MISSION PROPOSAL TO THE
EUROPEAN SPACE AGENCY

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Proposal to the European Space Agency for an

INFRARED SPACE OBSERVATORY

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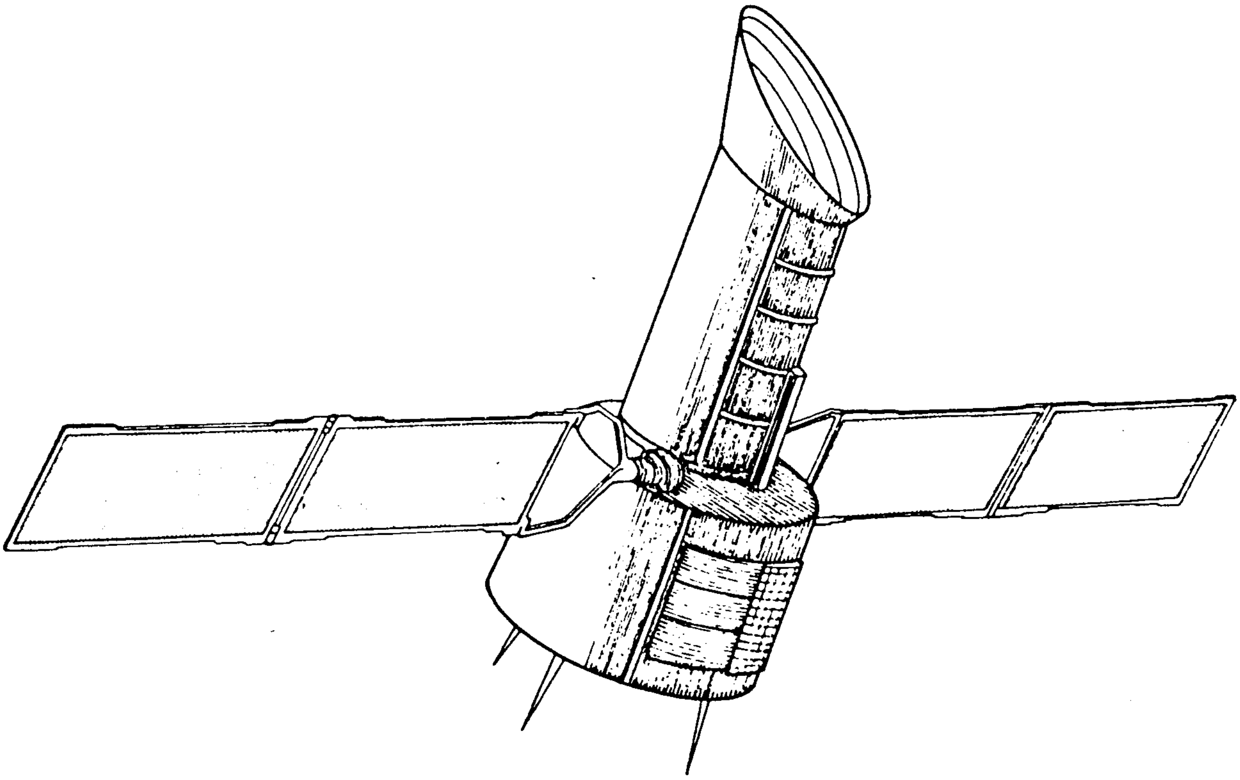

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1. SUMMARY.

The Infrared Space Observatory (ISO) is proposed as a 3-axis stabilized spacecraft carrying a one metre cryogenically cooled infrared telescope with a cryogen lifetime of ∼ 1½ years. A variety of instruments can be accommodated. A model payload has been considered which consists of a near infrared camera (1-5μ) a high resolution Fourier spectrometer ($\lambda/\Delta\lambda \sim 10^5$, 1-25μ) and a photometer (1-200μ). The scientific aims are primarily directed to infrared astronomy. However some consideration has been given to the possibility of carrying out studies of the earth's atmosphere using the complement of cooled instruments towards the end of life of the cryogen. In addition, it is proposed that serious consideration should be given to extending the life of the mission, and the scientific objectives, by including a sub-millimeter heterodyne receiver. Such a system would offer an extremely interesting additional research potential in astronomy and in atmospheric physics.

The observatory is designed to provide facilities for studies of diverse astrophysical objects, ranging from extragalactic systems, large scale galactic structure, molecular clouds and star formation regions, HII regions, evolved stars, planetary atmospheres and cometary studies. The extragalactic studies are expected to be particularly important in the ST era. The sensitivity of ISO is such that, for normal galaxies with no infrared excess, the near infrared photometric sensitivity will be comparable to that of existing photographic sky surveys in the visible. Another important activity will be the detailed study of objects resulting from the IRAS sky survey. ISO will have better angular resolution than IRAS, reducing source confusion, the same or higher sensitivity, and an instrument complement which will permit a thorough spectroscopic and photometric study.

The choice of a cryogenic telescope ($T < 40^{o}$K), in preference to an uncooled telescope, and the decision to concentrate on the wavelength range below 120μ was made on the basis of two main factors. (i) The scientific interest in this wavelength regime, which is particularly rich in molecular, atomic, ionic and solid state transitions, a study of which provides insights into a whole range of astrophysical phenomena. (ii) The recent developments in infrared detector technology which have led to an improvement of at least two orders of magnitude in detector performance for $\lambda < 120\mu$ compared to the bolometer detectors which are used for $\lambda > 120\mu$. The situation now is that a space infrared telescope cooled to $T < 40^{o}$K and coupled to modern photoconductor detectors gives a sensitivity which is approaching the limit set by the zodiacal light background. This enormous gain in sensitivity has occurred at the same time as the technology has provided two dimensional detector arrays of similar high sensitivity, which will allow imaging in the near infrared (1-5μ).

ISO is planned as an observatory operating essentially in real time, to be used in a similar way to IUE by astronomers whose observing proposals have been accepted by ESA. Access to ISO on this basis will be open after an initial 3 months commissioning phase by the ISO Instrument Science Teams.

A comparable infrared cryogenic telescope system (SIRT-F) is under active study by NASA and a smaller diameter (50 cm) cooled telescope for astronomy and astrophysics (GIRL) is being developed in Germany. Both of these are short duration missions intended for Spacelab flights. GIRL in particular will be an important precursor to a spacecraft observatory, carrying out exploratory studies which can be followed up by the more powerful ISO.

As already pointed out by the ESA Scientific advisory groups, in the 1980's the future of European astronomy must rest in large measure on large observatory class satellites if it is to remain competitive. The science that can be accomplished with ISO is outstanding and will make a major impact in astrophysics. It is hoped that this proposed mission can be studied in depth.

2. INTRODUCTION TO ISO.

Infrared astronomy has developed to the point where further progress in most groundbased observations becomes limited by the atmospheric absorption and by emission from the warm telescope and the atmosphere. The limitations in the wavelength coverage to a few atmospheric windows makes many classes of interesting objects and phenomena inaccessible to groundbased observations. For this reason infrared telescopes are now used in aircraft, balloon gondola and rockets. Increasingly interesting results have been reported in the astronomical literature in the last few years covering a wide range of astrophysical phenomena observed by these first generation 'space' telescopes.

A crucial step in the development of infrared astronomy will be made with the all-sky infrared survey by IRAS 1981/82. The present very poor coverage of the sky in the infrared will be remedied by IRAS to a sensitivity level which is comparable to that achieved in the radio regime. Other space infrared projects are in the planning (SIRTF) or development (GIRL) phase. Both of these use a cryogenic telescope which will be flown on the Spacelab.

The proposed Infrared Satellite Observatory is a timely and necessary extension of the observational capabilities in the infrared after this initial exploratory phase. The 1½ year mission will allow time for the full exploitation of the enormous gains that the space environment offers to observations in this wavelength range. The 1 meter class telescope of ISO provides an angular resolution which ties in naturally with ground based near-infrared observations and mm-radio observations. Cooling the telescope to $T < 40$ K and using detectors of NEP $\sim 10^{-17}$ W $\sqrt{Hz}$, provides a sensitivity better or as good as in IRAS and allows follow-up observations on sources discovered in the IRAS survey. The proposed wavelength-range of the model payload covers the range from $1\mu m$ to $200\mu m$ thereby allowing for a meaningful tie- in with existing observing systems. If the proposed extension of the use of the telescope to submillimeter wavelengths is feasible, the capabilities of ISO would be enhanced even further and extremely interesting research in atmospheric and interstellar molecular physics becomes possible.

During the early stage of consideration of an infrared project proposal there was a good deal of discussion on the question of proposing, as a free flyer, a large uncooled telescope for spectrosocpy (i.e.) a LIRTS free flyer. This idea was abandoned for two reasons. First it was seen that the recent improvements in detector performance for $1\mu < \lambda < 120\mu$ provide for unrivalled sensitivity when coupled to a cooled 1 metre telescope in space. Secondly, as indicated in Figure 1, that wavelength range between 1 and 120μ encompasses the region where transitions due to vibration and vibration-rotation occur in molecules and solids and where fine structure lines due to atoms and ions are predominant.

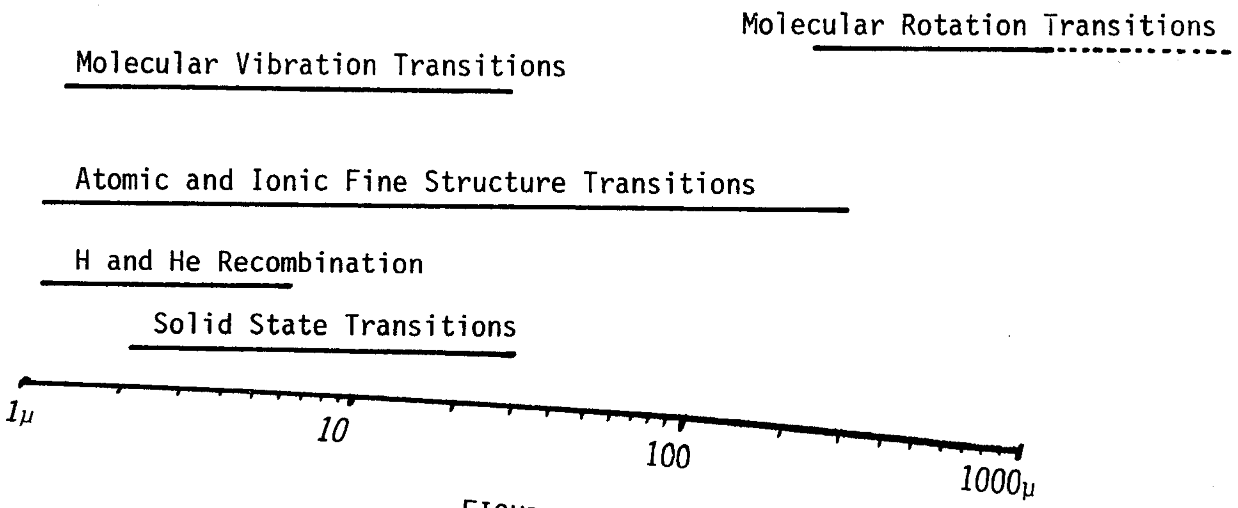


FIGURE 1

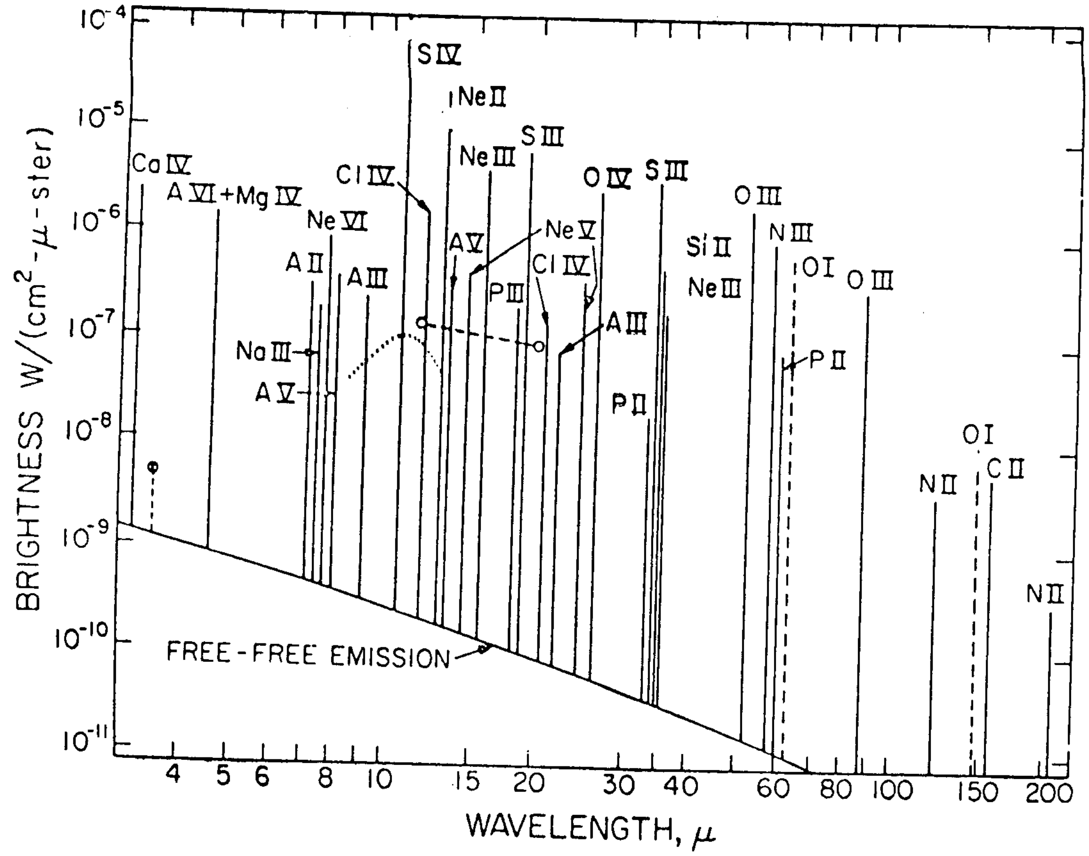


FIGURE 2

Figure 2, (from Petrosian), shows the many lines in this region just due to atomic and ionic fine structure transitions. Clearly, the use of a system such as ISO gives access to a very wide range of transitions and hence provides a probe to a diverse range of physical environments in astronomy. By contrast, the longer wavelength regime is much more restricted. There is no doubt that a mission, using a large uncooled telescope, would be valuable, but if such a telescope is to be proposed it should be larger than was foreseen for LIRTS and it should concentrate, unlike LIRTS, on the long wavelength region, since detector limited sensitivity is only reached for $\lambda \leq 2\mu$ or $\lambda \geq 120\mu$. Figure 3 shows the situation for various values of detector NEP. A value of 10^{-17} W/$\sqrt{Hz}$ is taken as representative of the state-of-the-art for $1 < \lambda < 120\mu$ and 10^{-15} W/$\sqrt{Hz}$ for $\lambda > 120\mu$.

Some submillimeter spectroscopy could be done with ISO. The suggestion is that a careful study be made to see if heterodyne receivers can be accommodated on ISO. Although the angular resolution would be limited, there is still a range of studies which can very usefully be done with such receivers once the cryogen has been depleted.

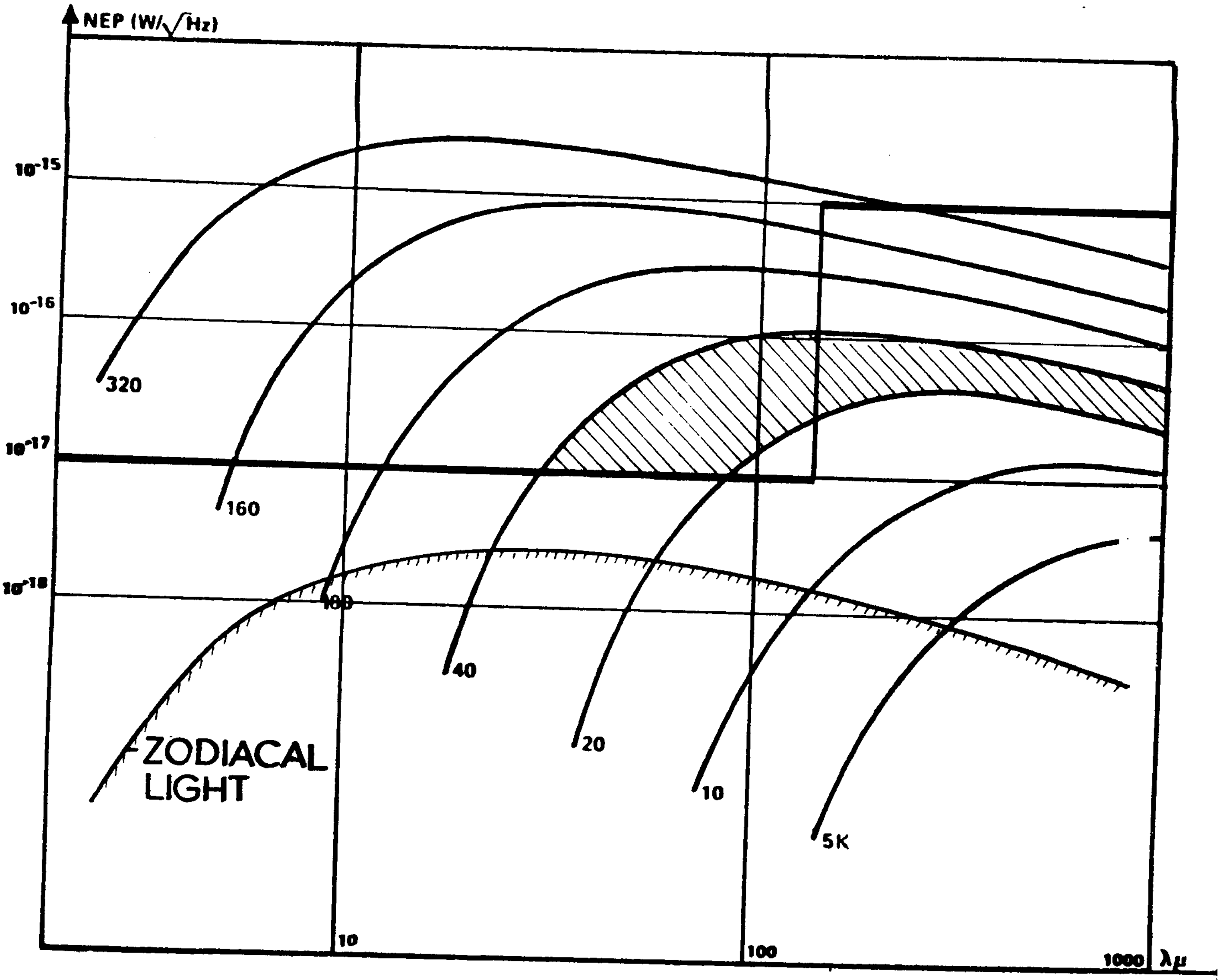


FIGURE 3

BACKGROUND NOISE EQUIVALENT POWER FOR A DIFFRACTION LIMITED TELESCOPE FOR DIFFERENT MIRROR TEMPERATURES. (A cold bandpass filter placed in front of the detector with $\Delta\lambda/\lambda = 0.1$ and an equivalent emissivity of 0.04 is assumed).

3. THE SCIENTIFIC OBJECTIVES.

Introduction.

Infrared astronomy has made very significant contributions in many areas of astrophysics during the past decade, despite the fact that this branch of astronomy is young and has hitherto been carried out with modest levels of manpower and finance. The reasons why such contributions could be made have their origin in the fact that the infrared region is rich in atomic, ionic, molecular and solid state transitions, providing a key to the study of chemical and physical conditions in a whole range of objects extending from planetary atmospheres to molecular clouds and gaseous nebulae. In addition cool objects, ranging from dust clouds and protostars through to late type stars, galaxies and the remnant cosmic background radiation, have their maximum emission in the infrared region.

By freeing such observations from the severe limitations on sensitivity and wavelength range imposed by atmospheric effects and warm optics and by permitting observatory type of operations over the 1½ year lifetime, ISO can be expected to make a very major impact on infrared astronomy and lead to important developments in astrophysics. A description of the main scientific astronomical objectives follows in sections 3.1 to 3.4.

If the addition of a submillimeter heterodyne system proves feasible, then an important programme in atmospheric physics and astronomy will also be possible. This is described in section 3.7.

3.1 Extragalactic Research.

The advantages of an infrared space observatory will be most clearly evident in the field of extragalactic research where further progress by groundbased observations is already limited by the Earth's atmosphere. With the 2-3 orders of magnitude increase in sensitivity achievable in space it will be possible to observe to cosmological distances and without restrictions on the accessible redshift ranges imposed by the atmospheric windows.

The sensitivity can be illustrated by noting that for normal galaxies with no infrared excess above the stellar continuum, the near infrared photometric sensitivity will be comparable to that of existing photographic sky surveys (Palomar, ESO, SRC). In the case of elliptical galaxies this will allow a significant study of their stellar populations via near infrared spectroscopy. The 1.9μ H_2O and 2.3μ CO bands, seen in absorption, are sensitive to both luminosity class and O/C abundance ratio. Of particular interest would be a search for evolutionary effects (e.g. dwarf/giant ratio) as a function of redshift which could be important cosmologically for refining the magnitude-redshift test.

There will be a strong interest in nearby galaxies which can be studied with angular as well as spectral resolution. Within 10Mpc of the Sun there are about 150 galaxies of all morphological types. Of most interest will probably be the spirals because of the possibility of studying star formation along the spiral arms. This will involve an application to more distant objects of many of the infrared techniques already successfully exploited within the Galaxy during the last ten years. These include broad-band mapping to determine the distribution of heated dust, recombination and fine structure line observations of the ionized gas around recently formed massive stars and searches for H_2 emission in the near infrared as evidence of shock front induced by spiral density wave effects. The nuclei of nearby galaxies, particularly those suffering high visual extinction, will also be of considerable interest.

The most dramatic results obtained so far using groundbased and airborne facilities have been for active galaxies. Seyfert galaxies and quasars exhibit an infrared excess above the stellar continuum which may be thermal, non-thermal or a combination of both. The Seyfert 2 galaxy NGC1068 radiates more than 90% of its total energy within a broad far infrared peak which is apparently thermal but is probably powered by an underlying non-thermal source. Seyfert 1 galaxies and quasars exhibit a smoothly rising spectrum through the infrared with no pronounced infrared peak.

Particularly in the far infrared however these conclusions are based on only a handful of observations obtained with airborne telescopes. From near and mid-infrared groundbased data on a larger sample of Seyfert galaxies Rieke has concluded that infrared and ultraviolet excesses are probably anticorrelated which means that currently available samples (selected for UV excess) are biassed against the most luminous infrared galaxies. It has been found also that the "normal" spiral galaxy NGC253 and the famous peculiar galaxy M82 are characterized by similar far infrared peaks to that of NGC1068. Due to the limited infrared sensitivity, all the observed galaxies are prominent optical objects and there is no reason to suppose therefore that they represent the most extreme cases of "infrared" galaxies. At least it appears possible to conclude that the dominant contribution to the energy output of several classes of galaxy lies in the infrared.

Until IRAS has performed its all sky survey we can only speculate about the existence of more extreme or currently unsuspected types of infrared galaxy. Even conservative estimates however predict the detection of around 40,000 galaxies with this satellite.

For the detailed study of active/infrared galaxies it is necessary to provide both for photometry in the far infrared (50-200μ), where the bulk of the energy is emitted, and for medium resolution spectroscopy in the near and mid infrared where it is possible to investigate the underlying physical conditions and dynamics. The near infrared in particular is rich in solid state, atomic and molecular features and even at the time the proposed facility flies one will still be seeking inspiration from the data as a guide to specific observational programmes. After many years of optical spectroscopy the nuclei of Seyferts, emission line galaxies and quasars are still largely a mystery.

One specific current problem relating to quasars which is amenable to infrared space observations is that of their anomalous recombination line spectrum. In a few cases where it has been possible to detect Hα and Hβ redshifted into one of the near IR windows, the ratio Lyα/Hα,Hβ is found to be roughly an order of magnitude smaller than predicted by recombination line theory and inconsistent with reddening by normal dust. Perhaps the most decisive observations of quasars however would be the detection of a stellar population (via the H_2O and CO bands for example) providing direct evidence of the nature of these objects as galaxy nucleii.

Speculating beyond even the redshift of quasars, the facility proposed could be used to perform a deep survey for primeval galaxies. In this area both positive and negative results provide important input into cosmological models. Existing theories predict the epoch of galaxy formation at $Z > 10$ and luminosities of $L \sim 10^{12} - 10^{13} L_{\odot}$ during a phase of rapid star formation. At this redshift the Lyman edge is at $\lambda > 1\mu m$ and while such objects are probably optically invisible they would be detectable with a few minutes of integration in the near infrared. The more difficult problem is that of identification which can only be foreseen now to be based on their expected small but finite angular size (1-5") and the possibility of observing the redshifted Lyman edge or other feature.

These few specific examples illustrate the versatility of infrared measurements to contribute in many diverse areas of extragalactic research. This is a rapidly changing field however and, particularly with the expectation of many surprises when IRAS flies, one should not anticipate too precisely the detailed observations which will take priority in 5-10 years time. The general need for the sensitivity advantages possible in space however are clear in this field and are essentially independent of the precise observations required.

3.2 Molecular Clouds.

Although the presence of large atomic hydrogen clouds in the galaxy and of ionized gas clouds close to young stars have long been known, it is only in the past few years that the total extent of the large cool clouds of molecular hydrogen has been established. The study of these interstellar molecular clouds using radioastronomy receivers at cm and mm wavelengths, has led to the identification of some 40 different molecules and their isotopic species within cloud complexes. Such clouds typically have temperatures less than 100K, H_2 gas densities between 10^3 and 10^6 cm^{-3} and are of extent up to $\sim$ 100 pc. The origin of the molecular hydrogen and of the complex molecules found within these clouds is a question which is the subject of active research at this time and likely to remain so for some years.

Mapping of these clouds has been done from the ground using the CO ($J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$) transitions at 2.6 and 1.3 mm respectively, since it has been established that CO provides a tracer for H_2. Information on the extent and energetics of such clouds has also been provided by measurements of the infrared continuum emission from associated dust. Such maps also delineate core regions containing young or proto stars and also HII regions, as discussed in 3.3.

In local high density regions of the clouds, where temperatures have been found to approach 3000K and where U.V. radiation exist, emission of the H_2 quadrupole rotation-vibration lines have been detected at wavelengths of 1.95μ and 2.42μ . As yet there has been no direct observation of molecular hydrogen in the cooler regions of clouds, via the rotational lines extending out to 28μ. The sensitivity of the ISO system will permit a meaningful search for these H_2 rotational lines and will allow greater sensitivity in measurements of the near infrared rotation-vibration lines and also of the continuum.

With the availability of a submillimeter heterodyne receiver many more molecular and atomic transitions will become accessible. In fact some of the essential molecular rotational transitions of light molecules, the hydrides (CH, OH, MgH, NH_3, PH_3, H_2O, etc.) are located in the submillimeter wave region. In addition higher rotational transitions of the most widely distributed molecules and their isotopic species such as CO, H_2CO, HCN, HCO^+, H_2S, and many others, are found there. Many of these transitions are expected to have high intensities. Some of the lines will become optically thin only in the far infrared region. It is the highly useful property of different molecular transitions that due to their varying intrinsic properties (such as excitation energy, transition probability) they probe different cloud regimes; for instance the expected dependence of the line intensity of different transitions of molecules like CO, H_2CO, on the cloud temperature. Once this wavelength region will be accessible to routine observations, one can truly expect an extremely rich harvest. A more complete determination of the excitation problem, will lead to a much broader and deeper understanding of the physical state of molecular clouds, their prevailing chemistry, their evolution and how these facts relate to star formation and to mass exchange between stars and the interstellar matter.

An important atomic line for study is that of neutral carbon, at 610μm and 369μm. It is expected that neutral carbon is a major coolant in low temperature neutral clouds having sufficient opacity to ultraviolet radiation which photo-ionizes carbon. Consequently it may initiate dynamical instabilities and collapse of the cloud to densities where other species take over this r The sensitivity of carbon to the opacity and evolutionary state of a cloud makes the determination of its abundance important in the understanding of the thermal, chemical and dynamical development of interstellar clouds.

3.3 Star Formation.

Far infrared photometry and mm wave molecular spectroscopy have yielded a basic knowledge of the massive, cold, progenitor clouds while near and mid infrared observations have revealed the presence of probably protostellar and more evolved compact objects within such clouds. In the case of the Orion complex the shock waves measured responsible for initiating the cloud collapse have been observed via the 2-4μm quadrupole-vibration band of H_2. We now have a scenario at least, for the formation of massive stars.

Even for massive stars however the details are unclear. The dynamics of clo collapse are not well understood - for example the relative roles of spiral density wave, HII or other shock mechanisms in the compression phase. The evolutionary sequence of the discovered compact objects is also not established in any detail. Until better near-infrared spectroscopy is possible it has ye to be confirmed that nay of the present candidates is genuinely protostellar.

Virtually no observational data is available on the formation of lower mass stars - partly because the sensitivity limit of groundbased systems has biassed results towards the most luminous objects. An obvious first goal of a sensitive space telescope therefore would be to determine the total stellar and protostellar content of representative molecular clouds by means of near and mid-infrared "photography" using an array camera. Such an instrument in space could be up to 10^7 times faster than present single detector mapping on the ground. This would provide a technique for determining directly the luminosity function of forming stars.

The evolutionary state and the physical conditions in the surrounding cloud medium would be a high priority goal of near infrared spectroscopy of the various embedded objects. Low resolution spectra yield information on the temperature and the composition of solid particles while the presence and conditions of ionized gas can be determined at medium resolution by searching for H and He recombination lines and the fine structure line of heavier ions. Simply determining the presence or absence of ionized gas with the highest possible sensitivity is crucial in distinguishing massive protostars from objects which may just have begun nuclear burning. Some objects will have evolved super-compact HII regions, not detectable by radio techniques, whose properties can be studied by near infrared spectroscopy.

For protostars it will be possible to study the local velocity field unambiguously by high spectral resolution measurements of molecular absorption bands, observed against the continuum emission of the object itself. This can be done, for example, using the prominent 4.6μm band of CO which lies close to the region of peak emission for a protostar at a temperature of 500 K. With a resolving power $\sim 10^5$, the rotational fine structure within the vibrational band can be resolved and as these transitions cover a range of optical depth, the velocity profile as a function of distance along the line of sight can be deduced. Such information is crucial for a critical test of dynamical collapse models.

3.4. Evolved Stars and HII Regions.

3.4.1. Evolved Stars.

Star formation, stellar evolution, and the cold interstellar medium are intmaterly realted, since stars are born in the dense gas-dust complexes, and it is the physical and chemical properties of these complexes which determine when and how star formation takes place. At the other end of a star's life, postmain-sequence evolution seems to feature phases in which a substantial amount of mass is returned to the interstellar medium by processes ranging from rather gentle winds, through puffs, to the cataclysmic events making up a supernova explosion. These phases of mass loss are generally accompanied by condensation of dust grains, and in some cases molecules, and the dust in this case becomes a shroud which prevents direct observation of the star itself in these stages of stellar evolution. It is only at infrared wavelengths that the underlying star does not remain hidden.

Moreover, in some cases, such as novae and the mass loss from cool stars, the actual formation of the dust grains can be observed as the post-maximum phase proceeds. Study of the various near infrared absorption and emission bands will allow an observer to follow the physics and chemistry of the formation processes of the interestellar dust grains in real-time.

3.4.2. HII Regions.

As is the case at radio wavelengths, HII regions are the dominant feature of the far-infrared sky. The difference is that it is thermal emission from dust grains which is observed in the infrared, and so radio and infrared observations are highly complementary in studying these regions. Not only do photometric maps of these gas-dust complexes in the infrared show the distribution of dust, heated by the ambient radiation field, but the optical properties of the dust itself also help to determine the local radiation field. Thus comparison of infrared, optical, and radio maps of these regions are essential in building up a complete picture of the astrophysics of HII regions. (Such mapping also allows identification of hot spots due to main sequence stellar, or pre- or post-main sequence stellar objects, and the measurement of some of their physical properties). The infrared radiation from dust in, and perhaps around, the HII region dominates the total luminosity of these sources, and permits determination of the bolometric luminosity of the exciting star(s). The energetics thus determined are not always simple: for example, in the case of 30 Doradus, the luminosity observed in the infrared requires a minimum of $\sim$ 80 05 stars to power the nebula. Infrared photometry, used in conjunction with free-free radio observations, permits a study of the ultraviolet and infrared optical properties of the dust grains, their composition, sizes and shapes, temperature, and the local ratio of dust to gas densities.

But infrared observations are also important in the study of the gas in the HII region as well. There are a great many infrared fine-structure lines due to various atomic and ionic species. The relative intensities of some pairs of these lines, for a particular ion, may be highly temperature-sensitive, while for other pairs of lines the relative intensities may be nearly independent of temperature and sensitive to the density, depending on the relevant transition probabilities and collision cross-sections. Thus infrared observations of these lines, used not only alone, but also in conjunction with optical observations of these forbidden lines, permits determination of elemental abundances, electron temperature and density, and the ionization structure of the nebulae. These results, in turn , provide information on abundance gradients and the chemical evolution of the galaxy, since such infrared observations are nearly free of extinction across the galaxy. This data also has obvious implications for the theory of nucleosynthesis and star formation-rates in the Milky Way, and also in other nearby galaxies in which observations of HII regions can be made.

3.5. IRAS Follow-up.

In 1981/82 the Infrared Astronomical Satellite (IRAS) will conduct an all sky survey in four wavelength bands between 8μm and 120μm (see table 1 for details). The sensitivity limit for all channels is around 10^{-19} W cm^{-2}. The IRAS mission design includes a high level of redundancy in sky coverage to achieve high reliability for detection of infrared sources.

In addition to the survey detector arrays the IRAS telescope focal plane also contains a low resolution ($R \simeq 20$) spectrograph, operating between 6.5 and 24μm. This instrument will measure spectra of the brighter sources in the survey mode. A diffraction limited two-channel far-infrared photometer is also included, which will be used in the pointing and raster scanning modes of the spacecraft for studies of specific objects.

Both the high sensitivity of the IRAS instrument and the all sky coverage will lead to the discovery of many new sources. In the domain of Galactic astronomy a large fraction of the IRAS sources will be hot spots in molecular clouds, presumably protostars.

While only very few extragalactic objects have sofar been detected in the far-infrared, the IRAS catalogue will contain many thousands of extragalactic far-infrared sources.

The IRAS survey will produce data in four broadband channels up to 120μm and at an angular resolution ranging from 1 to 4 arcminutes. To study IRAS sources one requires expansion of the wavelength range to 200μm (when possible even to 1 mm) and to shorter wavelength (below 10μm). In addition, better angular resolution is required to resolve marginally or unresolved IRAS sources. Such extension of wavelength range and angular resolution can be provided by the proposed instrumentation in ISO. To achieve effective follow-up, the sensitivity of the proposed system should be at least as good as IRAS. This basic requirement is satisfied by the use of a cold telescope in the initial phase of the ISO mission.

TABLE 1 - IRAS CHARACTERISTICS

Survey

μm	Type	detector f.o.v. (arcmin)	NEF (W/cm^2)	NEF Jy
8.5 - 15.0	Si : As	0.75 x 4.5	3.6 10^{-19}	0.024
19.2 - 30.2	Si : Sb	0.75 x 4.5	3.2 10^{-19}	0.056
40 - 80	Ge : Ga	1.5 x 4.7	1.6 10^{-19}	0.042
83 - 119	Ge : Ga	3.0 x 5.0	0.7 10^{-19}	0.064

Spectrometer

μm	Resolution ($\lambda/\Delta\lambda$)	Detector	f.o.v.
6.5 - 13.0	20	Si : Ga	5 x 6 arcmin
11.5 - 24.5	20	Si : As	7.5 x 6 arcmin

Photometer

μm	f.o.v. (arcmin)	Detector
45 - 63	1.2	Ge : Ga
81 - 116	1.2	Ge : Ga
5 - 8	0.25	Si : As

3.6. Planetary Observations.

Introduction.

Infrared observations of solar system objects, using a space observatory, are likely in the future to be concentrated on the outer planets, Jupiter, Saturn, Uranus and Neptune, and on comets and asteroids. A discussion of the contributions expected to be made by ISO to a deatiled study of the Jovian atmosphere is presented below. Apart from atmospheric studies in a dynamic sense, there is considerable interest in a detailed analysis of the atmospheric constituents of these planets and of the gaseous and solid content of comets since each of these is likely to provide clues as to the original chemical composition of the primitive nebula out of which the planetary system evolved.

The instrumental requirements for such studies are primarily for near and mid-infrared spectroscopy with high resolution capability for molecular line measurements. Lower resolution measurements over the same wavelength region will provide for spectra of cometary dust and surface mineralogical studies of asteroids and satellites. The high sensitivity of the ISO system will enable better measurements of minor atmospheric constituents to be made and provide also for a significant improvement in spectroscopic studies of comets through measurements of the associated molecular emission in the low temperature regime at large distances from the sun.

3.6.1 Near Infrared Spectroscopy of the planets.

This wavelength range is very attractive and promising in the case of Jupiter and Saturn to study minor atmospheric constituents. The region can be separated in two spectral ranges: 1-4μm and 5μm.

a) λ = 1-4μm.

This region corresponds to the reflected solar radiation and contains transitions of CH_4 and NH_3 molecules and their isotopes which account for most of the opacity. This wavelength region has been extensively studied from the ground. A spectral resolution of 0.05 cm^{-1} has only been achieved by the interferometer of Connes mounted on the 5 m telescope at Mt Palomar (Connes and Michel, 1974). High resolution spectra obtained in space and therefore free of telluric absorption would provide additional and perhaps new information on column abundances of methane and ammonia above the reflecting layer in the planetary atmosphere. Constraints on the modelling of radiative diffusion in the upper layers of these planets will result from such observations. Several windows in the Jovian spectrum were identified by Danielson (1966) from low resolution spectra taken at an altitude of 25.6 km. Exploration of these windows around 1.9μm and 2.7μm, which are masked by telluric absorption, will yield information on trace elements known to be present under the cloud top level.

b) The 5μm planetary atmospheric window.

This window is fee of H_2, NH_3 and CH_4 absorptions. The emission at these wavelengths from 4.4 to 5.5 μm is located in the so-called "hot spots" which corresponds to the sounding of deep levels, where T = 300 K, through the clearings of the Jovian cloud cover. Many trace elements have already been discovered or possibly identified in these hot spots.

The detection and studyof line parameters of the transition exhibited by such molecules are fundamental tools in the understanding of Jovian chemistry.

3.6.2. Mid-Infrared Spectrophotometry.

This spectral interval contains two major planetary atmospheric windows (8-14µm), 17-25µm), the exploration of which has already provided very important results in planetary atmospheric studies over the last two decades.

Molecular hydrogen opacity is dominant between 17 and 30 µm. This was used to derive the thermal structure of the atmospheres of Jupiter, Saturn, Uranus and Neptune. The relative abundances of H and He in Jupiter were also derived from measurements made at these wavelengths. In addition to the thermal radiation of the planet, transitions of various molecules are seen either in absorption or in emission. This spectral range would be of special interest for the study of both the thermal structures of the giant planets and Titan and the determination of column abundances/distribution profiles of molecules such as CH_4, NH_3, PH_3, C_2H_6, C_2H_4, C_2H_2. This interest is greatly enhanced in the cases of Titan, Uranus and Neptune since very few spectroscopic data are available today. Furthermore, no space probe missions to these planets are planned in the coming years.

3.6.3. Far Infrared Photometry.

The main objectives envisaged in this wavelength range are measurements of the thermal fluxes of Titan, Uranus and Neptune.

Three bands can be defined for this purpose:

30 - 35 µm	(280 - 330 cm^{-1})
35 - 45 µm	(230 - 280 cm^{-1})
45 - 200 µm	(50 - 230 cm^{-1})

In the case of Uranus, these bands allow the sounding of atmospheric layers in the ranges, respectively:

100 - 250 mb
250 - 400 mb
400 - 500 mb

In Neptune, these levels are slightly shifted towards greater pressure, but the sampling of the thermal structure is comparable (Courtin et. al., 1979).

Assuming a black-body emission with T = 57 K, 20% total transmission and a detector-NEP of 4×10^{-14} $W/\sqrt{Hz}$, a signal to noise ratio of 100 could be achieved with integration times t ∿ 3 mn, t ∿ 5 s (for Neptune, these figures are to be multiplied by a factor of 4, due to the smaller apparent diameter).

Emphasis should be placed on the great interest of achieving repeated measurements of the radiation of Uranus since between the years 1985 and 1992, Uranus' axis of rotation will move away by an angle of about 50°, from a position pointing towards the Sun. Very exciting information on planetary dynamics can be expected from the type of response that the atmosphere will exhibit to such drastic changes in solar illumination.

In the case of Titan, we expect that observations in all three channels will be possible since the diffraction limited field of view of a 1 m aperture telescope will not contain the Saturn/Rings system, provided that Titan has a maximum elongation at the time of observation.

Finally, it must be remarked that high resolution ($\Delta\sigma \sim 0.5$ cm^{-1}) studies in this range of the pure rotational transition of NH_3 in the spectrum of Jupiter, will be valuable since those observations are severely contaminated by telluric absorption by water vapour even from airborne observatories. Another target for such spectroscopic measurements would be the detection of minor constituents in Saturn such as PH_3 and also the study of the ring emission.

Submillimeter heterodyne detection techniques have already been successful in the area of planetary observations, especially for the detection of CO_2 in Venus and Mars atmospheres. Such a system would be valuable in a search for trace constituents which exhibit transitions in the submillimeter range (CO_2, NH_3, PH_3, HCN, CS, HCl, HS) especially in the atmospheres of Jupiter and Saturn.

3.7 Atmospheric Sounding.

3.7.1. Introduction.

The atmospheric region between 10 and 100 km called the middle atmosphere is comprised of the stratosphere and mesosphere. Our present understanding of this part of the atmosphere is very incomplete. The large consideration given to this extremely important portion of the atmosphere is demonstrated by the Middle Atmospheric Programme (MAP), a major international cooperative effort, planned for 1982-85 time frame. MAP will coordinate research activities in different fields such as theoretical studies, modeling, data interpretation and data collection from groundbased, airborne and spaceborne platforms. An atmospheric experiment as proposed here will be of crucial importance in the data collecting step for MAP. Of course, the observational programme and the time of launch has to be coordinated with the numerous other activities already under way for MAP.

A submillimeter heterodyne receiver experiment will substantially extend the global stratospheric and mesospheric measurements performed by the very successful series of experiments (SCR, PMR, LRIR) on the NIMBUS 4, 5 and 6 satellites, on the NIMBUS-7 satellite (SAMS, LIMS), and future experiments planned for Spacelab missions (FSLP and DM-2), and by the Upper Atmospheric Research Satellites (UARS).

To our knowledge this is the first time a sub-mm-sounder will be available for atmospheric research. Experiments flown earlier or proposed for future missions are restricted to the infrared and mm-wave portions of the spectrum. To open up the submillimeter-wave region for atmospheric research will permit measurements of the atmospheric parameter with higher accuracy and allow additional investigations not possible earlier.

3.7.2. Objectives.

The main objective of an atmospheric sensor is to enhance our understanding of the atmosphere between 10 and 100 km. A wide range of parameters are involved in basic processes of the stratosphere, mesosphere, and lower thermosphere which are not well understood. These parameters, furthermore, have wide variations in both space and time. A paramount consideration in proposing this experiment has been the need that as many as possible of the relevant parameters can be measured at the same place and time. For example, the measurement of important minor constituents involved in the ozone chem such as O_2, O_3, O, NO, N_2O, H_2O, H_2O_2, OH, and many others.

A list of possible scientific problems to be studied and answers given by a combined mm-wave, sub-mm-wave experiment is given below.

Scientific problems	Contribution of an atmospheric limbsounder (as a function of space and time).
1. What are the variations of temperature in the mesosphere and lower thermosphere?	Kinetic temperature
2. What are the factors controling radiation loss by the 15 µm bands of CO_2, the major energy sink in the region?	Kinetic temperature
3. What other energy exchanges occur in the mesosphere and lower thermosphere?	O_2 distribution O_2 rotational temperature
4. What is the interaction between chemistry, radiation and dynamics in the mesosphere and lower thermosphers?	Measurements in 3 above and distribution of H_2O, CO, O_3, O, NO, etc.
5. What is the influence of minor constituents on stratospheric chemistry?	Distribution of: O_3, NO, N_2O, CH_4, CO, H_2O, ClO, $CFCl_3$, CF_2Cl_2
6. What are the detailed dynamics of the stratosphere, mesosphere, and lower thermosphere? How do the transfers of energy and minor constituents occur?	Distribution of minor constituents which are principally inclueneed by the atmospheric motion field, Measurement of the component of wind velocity in the observation direction.

During the last few years techniques of numerical modeling have been extended upwards from the lower atmosphere and have been applied to the stratosphere and mesosphere. These models are of very differing degrees of sophistication; the most elaborate of them attempt to treat the chemistry and the distribution of minor constituents, the radiation field and the large scale dynamics as full three-dimensional time dependent problems. It is through comparisons of the results of such models with detailed sets of observations, such as proposed here, that our understanding of this region of the atmosphere will develop.

In order to obtain the required height resolution, the limbsounding principle has to be applied. For this observing scheme the ultimate height resolution due to radiative transfer is ∿ 1-3 km. Therefore, the orbit and the antenna have to be chosen accordingly. The height resolution obtainable with a 1.2 m diameter antenna for a 900 km orbit is sufficient. The horizontal resolution due to radiative transfer is 200-400 km. Thus a 100 km horizontal resolution normal to the line of sight is reasonable. For those channels with a spectral resolution comparable to the Doppler line width, the horizontal resolution must be less if the effects of Doppler shift due to orbital motion are to be removed. Therefore, measurements with channels having spectral resolution comparable to the Doppler line widht will be affected by orbital motion if their horizontal beam-width at tangent point is larger than ∿ 10 km, even though the observations are in a direction normal to the orbital velocity.

For the measurements the antenna will scan over an angle of less than 10° in steps of the order of 0.001° at a maximum of 0.001 seconds per step. The vehicle attitude must be such that the experiment can view the limb during the experiment operation. The satellite yaw angle must be within ± 5° of 0° or 180° in order that orbital motion does not shift the frequency of the spectral lines outside the frequency range of the receivers. For an orbit altitude of 250 km the following stabilities are required:

- stability of 0.01°/s in all axes is adequate
- absolute accuracy of ± 0.5° in all axes is adequate for conducting the experiment
- an absolute knowledge of the yaw angle to an accuracy of $\lesssim$ 0.3° is desirable to obtain atmospheric winds.

For orbit altitudes larger than 250 km the pointing requirement is higher, but the planned 1 sec of arc pointing stability will be adequate for all orbits acceptable for limbsounding with antenna diameters less than 2 meters.

Spectral resolution or selection is required of limb sounding instruments in order to identify emission from a particular gas. For heterodyne instrumentation arbitrarily fine spectral resolution can be achieved by means of electronic filtering (filter bank, digital correlators or optical correlators) after the signal has been converted to a sufficiently low frequency by mixing it with a local oscillator. The major requirement on the instrumentation for spectral resolution is then that the local oscillator frequency be sufficiently stable that its variation does not smear the resolution by an unacceptable amount. Such stabilities are readily achievable. Given this arbitrarily fine spectral resolution the ultimate limit on signal detectability of microwave radiometers is due to unaccounted for spectral responses in the instrument. In practice these effects can generally be reduced to $\sim 10^{-3}$ to 10^{-4} of the value of the input signal for the instrument bandwidths to be used in atmospheric sensing. Thus, the major limitation on the MLS measurements is expected to be the sensitivity of the radiometer. Today's state of the art in receiver technology allows the construction of uncooled, all solid state and space qualified receivers up to 300 GHz with single sideband (SSB) noise temperatures less than 500 K to 5000 K for frequencies 100 to 300 GHz respectively. For useful atmospheric measurements in the sub-mm region receivers with SSB-noise temperatures less than 10.000 K at 1000 GHz are required.

Finally, it should be mentioned that if the telescope was available for atmospheric measurements using the cooled Michelson system, it would be possible to carry out near infrared measurements of a range of constituents which would include:

Species	Wavelength (μm)	Required Observation Geometry	Required Spectral Resolution	Emission (E) or Solar Occultation
Stratospheric H_2O	6.3/25	Limb Sounding	5 cm^{-1}	E, S
Stratospheric O_3	9.6	" "	5 cm^{-1}	E, S
Temperature (CO_2)	15	" "	10 cm^{-1}	E, S
HNO_3	11.3	" "	1 cm^{-1}	E, S
FC	10.8 11.8	" "	1 cm^{-1}	E, S
CH_4	7.7	" "	1 cm^{-1}	S
N_2O	7.8	" "	1 cm^{-1}	S

4. THE TELESCOPE AND EXPERIMENT SYSTEM DESIGN.

Introduction.

The fundamental parameters in the total design of an infrared observatory are the diameter of the telescope primary mirror and the operating temperatures of it and the other optical components. Everything else in the design hinges on these two factors. From the science aspect, sensitivity and angular resolution demand as large a primary mirror as possible operated at a temperature which is consistent with the limits set by detector performance and the zodiacal background light. From the preceeding discussions and Figure 3 it is evident that with typical detector NEP's of 10^{-17} W/$\sqrt{Hz}$ at wavelengths less than 50μ a mirror temperature below 40^{o}K is necessary. Taken together with the requirement for detector operating temperatures below 10^{o}K, this leads to a requirement for either solid hyrogen or liquid helium as the cryogen.

The optimum size of the primary mirror is probably the most difficult problem in the design. Other studies (e.g. SIRT-F) indicate that the mass of the total telescope assembly increases as roughly the square of the telescope diameter, up to d ∿ 150 cms, where a transition from a beryllium primary to Cervit becomes necessary. An increase in cryogen mass will follow of course as the aperture loading increases with diameter and the parasitic inputs through enlarged strut supports and increased surface area. Engineering and thermal design complexity will also increase rapidly with the size.

At this level of definition it can be stated that a primary mirror diameter of 100 cms would provide adequate sensitivity and angular resolution to allow most of the scientific objectives presented here to be reached on the basis of a 1½ year mission duration. At the same time it leads to an all-up spacecraft mass which is consistent with an Ariane launch into a highly elliptical or geosynchronous orbit.

In order to illustrate the potential of an infrared observatory of this type, a model experiment payload was studied. This comprised of three basic elements. First, an indium antimonide 1000 pixel array camera with a 1 arc minute FOV operating in the 1 to 5 micron region. In addition to band pass imaging, this would also be used to calibrate and periodically check on the infrared optical axis and the pointing system.

High resolution spectroscopy in the important 1 to 25 micron region would use a fast scan Michelson system of resolution up to 10^3. Due to the low temperature optical system this instrument could be used efficiently in a wide bandwidth mode. The third instrument is a photometer unit which is considered to operate from 20μ out towards 200μ.

A good deal of discussion on instrumentation and objectives centred on the question of carrying out heterodyne astronomy and also earth atmospheric physics measurements on completion of the astronomy programme. There are two aspects to this. First, the feasibility and value of a programme which would use the complement of cooled instruments to observe the atmosphere, starting at a point where the cryogen supply is almost exhausted. The input of > 5 watts into the telescope would require that the cooling gas to the telescope optics and baffle be cut off and the telescope allowed to warm up. Obviously, the situation is not ideal but it may be feasible to carry out a programme of worthwhile atmospheric physics by this means. It was felt that this possibility deserves detailed study. Likewise the question of adding a submillimeter heterodyne receiver was one which was felt to require a good deal more study and further justification. The advantage of an increased mission lifetime, after the cryogen has been used, to carry out high resolution line spectroscopy in astronomy and atmospheric physics, must be carefully weighed against an appreciable increase in complexity.

4.1 Telescope Design.

The table below presents a summary of the main features of the telescope system.

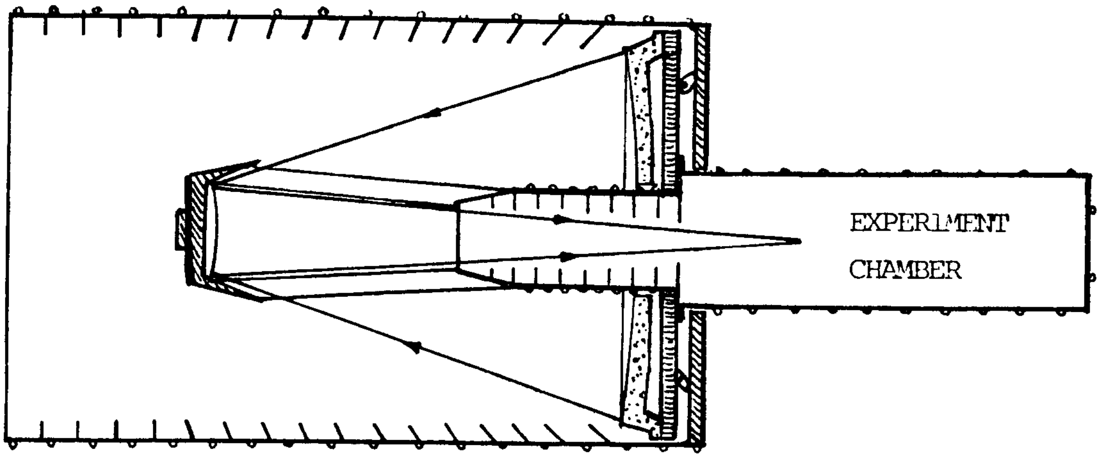
ISO - TELESCOPE OPTICAL CHARACTERISTICS

TELESCOPE - CASSEGRAIN F6.5 FIXED SECONDARY
PRIMARY DIAMETER, 100 cms SECONDARY DIAMETER, 28 cms
FOCAL RATIO : 1.5 PRIMARY , 2.0 SECONDARY
LINEAR OBSCURATION 38% , WITH SECONDARY SHIELD
TOTAL FIELD OF VIEW , 10 ARC MINUTES
PLATE SCALE : ∿ 20 ARC SEC/mm
QUALITY : DIFFRACTION LIMITED AT 5 MICRON
GEOMETRICAL ABERRATIONS : < 1 ARC SEC IN CENTRE OF FIELD
BAFFLING : OUTER, REJECTION FOR $> 60^{o}$ OFF-AXIS
INNER, NO PRIMARY ILLUMINATION FOR $> 30^{o}$ OFF-AXIS

The decision to use a fixed secondary and a 10 arc minute FOV with the Cassegrain system simplifies considerably the mechanical, optical and thermal design of the telescope, although the fixed secondary does add some complexity to the design of the photometer. The cheapest route is to use a classical Cassegrain (parabola-hyperbola) for the optics but the limitation in performance due to coma indicates that to meet the requirement on aberrations, it may be necessary to use the Ritchey-Chretien form.

The requirement for as small a central obscuration as possible and hence the absence of a secondary shield, has to be weighed against the demand to keep the telescope as short as possible, thereby limiting the possible extent of the main baffle and hence the degree of off-axis rejection.
In the schematic of the optical system shown below, a shield with a diameter of 38 cm is incorporated in order that the secondary mirror cannot receive radiation scattered from illuminated baffles in the main tube.
A third baffle, within the obscured area of the primary, is incorporated to reduce scattering and diffraction into the beam exit direction. This baffle will be cooled to a temperature close to that of the experiment chamber.

The primary and secondary mirrors should be manufactured from beryllium, which provides a lightweight mirror with good mechanical and thermal properties and which can take a surface polish down to about 0.01 μ in stress relieved material. In order to minimize the problems of stress and distortion on cooling the optical system, it is foreseen that the secondary mirror unit will be attached to the beryllium final baffle tube by Be struts. This final baffle will be fastened to the Be primary mirror support plate. Similarly, the strut supports for the experiment chamber should also be of beryllium and attached directly to the beryllium support plate, as shown below:



Schematic of the telescope assembly.

Thermal control of this optics assembly is by gas cooling coils around the primary mirror support, the baffle/strut system, and the experiment chamber. Attachment of this assembly to the aluminium 'strong ring' is by means of three flexing joints whose lines of action intersect at the optical axis. In addition, local support to the mirror will use three universal joints to take up rotational motion resulting from misalignment or fabrication errors.

The main baffle tube is fabricated from honeycomb aluminium and attached directly to the strong ring. Support of the baffle at the top is by glass fibre struts to the outer pressure vessel. At the lower end, the strong ring is fastened directly onto the cryogen tank top plate which is in turn supported by a glass fibre strut system to the outer pressure vessel.

Apart from minimizing distortion on cooling, the aim of this telescope design is to allow the fabrication and test of the complete optics unit independent of the rest of the spacecraft and the cryostat.

4.2. The Model Payload.

The main characteristics of the three experimental systems are summarized in the following table:

ISO - MODEL PAYLOAD CHARACTERISTICS

INSTRUMENT	λ RANGE	RESOLUTION	$T^{o}K$	FOV	DATA RATE	SIZE CM
1000 PIXEL InSb ARRAY CAMERA	1-5 μ	5	10	1'	10kb/s	5 x 5 x 5
FAR I.R. PHOTOMETER	20-200μ	3	5	2'	20kb/s	30x20x20
MICHELSON INTERFEROMETER	1-25 μ	$\leqslant 10^5$	50	30"	20-100 kb/s	60x30x30

4.2.1. High Resolution Spectroscopy, 1-25μm.

The reduction of the background due to cooling of the optics and the focal plane instrumentation will make Fourier transform spectrometers unrivalled in terms of sensitivity and will allow full exploitation of the other advantages of this kind of instrument: large optical throughput, broad wavelength coverage, compactness, absolute wavelength calibration, adjustable spectral and angular resolution.

From the technological point of view the construction of an instrument like the one briefly outlined in the following should not require major developments, as Michelson interferometers have already been used in space. There are examples of Michelsons cooled to low temperature and the resolving power required in this application is well below the maximum obtained in ground-based instruments. On the other hand the combination of cooling, space qualification, relatively high resolution and large wavelength coverage will certainly result in a quite complex design. At the present stage only the basic requirements will be listed with the idea of identifying performances and possible problem areas.

COOLING: A Temperature of $\sim$50 K is adequate to keep background photon noise well below $10^{-17}W/\sqrt{Hz}$ over the entire wavelength range 1-25μm and for 0.5 arcmin field of view.

WAVELENGTH COVERAGE: The basic limit for a Michelson arises from the efficiency of the beam splitter and needs a detailed study. By using two different beam splitters it should be possible to cover the 1 to 25μ region. Using dichroics or a prism one could then feed detectors having the appropriate spectral response. The double output of a Michelson becomes an advantage as it allows for complete coverage in wavelength by shifting the boundaries of the wavelength separation at the two outputs.

RESOLVING POWER: A resolution of $\Delta\sigma \simeq 0.05$ cm^{-1} ($R \simeq 10^5$) at 2μ would require $\sim$ 10 cm of movement and would be compatible with reasonable size of the optical elements ($\sim$ 5 cm) and reasonable collimator focal length ($\sim$ 50 cm) allowing for fields of view up to 20 arcsec.

MODE OF OPERATION: Fast scanning seems the right choice to reduce to a minimum the time per scan.

For detectors working at $\sim$ 100 Hz a scan would require $\sim$ 20 minutes at maximum resolution and short wavelength.

DATA HANDLING: A data rate of the order of 20 K bit/sec can be expected from the Michelson.

SENSITIVITY: Assuming a detector NEP of $10^{-17} W/\sqrt{Hz}$, 1.0 m aperture for the telescope, observing time of 20 min and total instrumental transmission of $\sim$ 10% one would get signal to noise $\sim$ 10 an unresolved line of about 5 x 10^{-21} W/cm^2.

4.2.2. Multiband Photometer/Camera.

Photometry has always played a central role in astronomy, and this is no less true in infrared astronomy than elsewhere throughout the electromagnetic spectrum. Thus a multi-band photometer should be a key focal plane instrument in the European infrared observatory. The design of the photometer is dictated by the general scientific objectives discussed above, and also its performance should improve on the photometric capabilities of previous infrared missions, viz. IRAS and GIRL. All these considerations lead to a photometer with the following features.

(a) Excellent photometric precision, especially for extended sources, by quasi-imaging cameras and perhaps by absolute chopping (contrasted with spatial chopping).

(b) Capability for long integrations on weak sources to achieve very high photometric sensitivity.

(c) Wide wavelength range, from one micron to at least 200 microns.

(d) Capitalize on the high photometric sensitivity and precision to make linear polarization measurements.

(e) Use the larger telescope aperture to achieve angular resolution at least to the diffraction limit of the telescope.

The parameters of a baseline photometer that fulfil these objectives are listed in table 2. The photometer is comprised of six detector arrays, each filtered so as to cover the one micron to 200 micron wavelength band. With the exception of the one to five micron InSb charge-coupled array, it consists of about 90 detectors in five arrays, each array covering about one octave in bandwidth. Virtually all elements of the photometer are now commercially available.

This photometer includes the following features.

(a) Photometry can be done with no moving parts.

(b) Absolute chopping can be done, optionally, by commanding on an electromechanically resonant tuning-fork type chopper. Such choppers operate reliably at cryogenic temperatures and are space-flight qualified.

(c) Pixel size is at the telescope diffraction limit for the long wavelength end of each array filter. The configuration of each array permits quick determination of the spatial extent of a source and some actual two-dimentional imaging.

(d) Dichroic filters allow observations using two arrays simultaneously: in addition a rotating filter wheel in front of the CCD arrays allows band selection in the 1-5 μm range (see 4.2.3).

(e) Measurement of linear polarization is achieved by commanding into the beam a rotatable (ca. one revolution per minute) wire-grid analyzer. One analyzer is required for arrays a and b, and another for the other three arrays.

TABLE I

Array	Waveband	Detector	Number	Linear Size	Field of view (arcmin)	Pixel Size (arcsec)
a	1-5 μ	InSb (CCD)	32 x 32	2 x 2 mm	1 x 1	1.5
b	10-25 μ	Si : As	33	5 x 6 mm	2 x 2	13
e	25-50 μ	Ge : Be	33	9 x 11 mm	4 x 4	25
d	50-100 μ	Ge : Ga	15	10 x 14 mm	4 x 6	50
e	100-200 μ	Ge : Ga	7	12 x 20 mm	5 x 8	100

4.2.3. 1-5μm Camera Array.

This device provides the capability for two dimensional imaging and for multiband photometry in the 1-5μm spectral range, it can also be used to determine the focal plane alignment relative to the spacecraft pointing system for the purpose of positioning the other instrument apertures (see 5.4).

The preliminary design proposed here is based on a fully developed InSb array. Infrared array technology is now progressing rapidly and the final selection will obviously be based on the current state of the art when the camera design is frozen. As the telescope is cooled, and the background consequently low, it is envisaged to mount the array directly in the focal plane and on the telescope axis. With 32x32 pixels of ≃ 50μm size, the field of view covered is ∿ 50x50 arcsecs and the resolution of 1.5 arcsec/pixel obtained with the selected telescope characteristics matches the diffraction limit at $\lambda = 3$ μm. A rotating wheel is proposed for positioning the required filters ($\phi \sim 3$ mm) in front of the array on command. These filters can be provisionally specified as the standard S,H,K,L and M photometric bands plus the 1.9μ H_2O and 2.3μ CO bands and a wideband 1-5μ filter. Filter manufacture for this spectral range presents no technological problems as multilayer dielectric filters are already routinely used in both groundbased and satellite instrumentation. Data outputs required are one video channel (10 Kbits/s), one pixel identification channel (TTL pulse) and the filter wheel position readout. The most important instrument parameters are summarized inthe table below:

Field of View	50 x 50 arcseconds
Resolution	1.5 arcsecs/pixel
N.E.P.	$< 10^{-16}$ W/$\sqrt{Hz}$
Filters	8-10
Array Area	2 mm x 2 mm
Instrument Size	∿ 5 x 5 x 5 cm
Mass	< 1 kg
Power Consumption	3W
Data Rate	10 Kbits/s (1 image/s)
Command	1 word (4 bit)

4.2.4. Submillimeter Heterodyne Spectrometer.

At wavelengths longer than 200µm, the Fourier transform and the Fabry Perot spectrometers cannot be considered suitable for obtaining very high resolving powers, and the use of a spectrometer utilizing super heterodyne detection techniques is imperative to achieve resolutions of the order of 10^6. Recent developments have made available key components for heterodyne spectrometry down to 500µm (750 GHz) and it now appears that the required sensitivity can be realized without major technological innovations. Many of the components have already been used in space communication satellites and a few submillimeter wavelength receivers are presently being used in airborne astronomy and atmospheric physics programmes. However minor development actions will be necessary on some individual components of the receiver to enable operation in a space environment. Fortunately most of these actions have already been started and are sponsored by the European Space Agency in its R and D programme.

It is proposed that the spectrometer includes two receivers, each having a local oscillator and a corresponding mixer-preamplifier. This arrangement will permit observations to be carried out in two different bands: 400-600 GHz, 600-750 GHz. This will provide the necessary redundancy of the key components. Most of the other items are common in both receivers: calibration loads, local oscillator power supply, intermediate frequency stage, multichannel spectrum analyzer,data processing system.

Each receiver consists of an ambient temperature Schottky barrier diode mixer. It is fed by two signals: one from the phase locked local oscillator (B.W.O., the other from the sky, arriving via input optics; both are combined via a quasi-optical diplexer. The intermediate frequency, containing all the information from the original spectrum is then amplified, again down converted and distributed to two radio frequency instantaenous spectrum analyzers.

RANGE OF POSSIBLE OBSERVING FREQUENCIES : A 400-600 GHz
B 600-750 GHz

INSTANTANEOUS BANDWIDTH : 500 MHz

SPECTRAL RESOLUTION : I SAW spectrum analyzer 50 MHz bandwidth, 1000 channels of 50 kHz (.025 Km/s at 600 GHz).

II Opto-acoustic spectrum analyzer 500 MHz bandwidth, 500 channels of 1 MHz (.5 Km/s at 600 GHz).

SENSITIVITY : S.S.B. noise temperature of receiver/telescope system $<$ 10.000 K for band A
$<$ 20.000 K for band B

DATA HANDLING : Highest data rate, expected during tuning and adjustment, 5 Kbit/sec; typically: 0.05 Kbit/sec.

The sensitivity of these receivers is such that a 0.5 K emission line arising from an extended object ($>$ 2 arcminute at 400 GHz) can be observed using the 1 MHz filters with an intergration time of one hour. This would be a typical observing requirement applicable to a minor molecular component in a cloud in the galaxy or to a major component in external galaxies.

5. SPACECRAFT SYSTEM CONFIGURATION.

5.1. Mechanical Design.

There are three main elements in the total spacecraft configuration. They are a) the telescope assembly, which includes the beryllium primary and secondary mirror and their support structures, the secondary shield and central baffle, the main telescope tube baffle and the experiment chamber; b) the main pressure vessel, with all of the cryogenic systems, the radiation shield and multi-layer insulation, the thermally isolating support struts for the cryogen tank and the upper support struts for the telescope baffle. It also includes the ejectable top cover for the telescope; c) the outer structures surrounding the vessel, which comprise the solar radiation shields, the solar arrays, and the spacecraft systems unit. The interfaces between three main elements are indicated in figure 4. Each of these elements will require particular and different types of expertise in design and fabrication. Hence the careful definitions of interfaces between each element is an important requirement for future study, so that the development of each element can then be carried out by the different groups or contractors with maximum autonomy.

Details of the telescope optics and structure are to be found in section 4.1. The whole of the telescope structure is anchored to the aluminium "strong ring" which is in turn attached to the top plate of the annular cryogen storage tank. Support of the whole telescope assembly and the cryogen tank is by means of glass fibre struts to the outer pressure vessel. The exact positioning of these, their number, size, and the question of whether some will have to be retracted after launch, form an important part of a detailed study. However, there is now a considerable body of experience to draw upon in designing such systems.

Vapour cooled radiation shields and multilayer insulation are interpositioned in the vacuum space between the telescope baffle - cryostat assembly and the inner wall of the aluminium pressure vessel, in order to reduce the parasitic heat input into the cryostat. It is assumed that the pressure vessel will have demountable vacuum joints at positions opposite the strong ring, at the position of the sun shield, and below the base of the cryostat. This will allow reasonable access to the struts and radiation shield supports. The outer surface of the pressure vessel supports the annular spacecraft system structure, comprising the attitude sensing and stabilization system, power conditioning and batteries, data handling system and the telemetry units. The external pipework, valving and associated cryostat control system would probably also be located in this housing. Since, in the present configuration, one side of the spacecraft will always lie toward the solar direction,the shaded side of the S/C systems housing will have any thermal radiation louvers that are necessary.

The section of the spacecraft exposed to solar irradiation will be covered by a highly reflecting solar shield which is thermally isolated from the pressure vessel. The aim is to keep the temperature of the wall of the pressure vessel as low as possible, since the final thermal input to the cryostat and telescope system will be strongly dependent on the temperature difference between the shields and the wall. For the same reason, the fixed aluminium sun shield is thermally isolated from those radiation baffles which extend out from the wall of the pressure vessel adjacent to the ejectable telescope cover. The intent is that this outermost baffle be cooled by passive radiation into space. Following ejection of the telescope cover, the next stage in baffling is provided by extensions of the vapour cooled shields, as indicated in Figure 5. The deployable solar arrays are stowed above the S/C housing. In the deployed configuration, the array has freedom to rotate about an axis perpendicular to the telescope axis.

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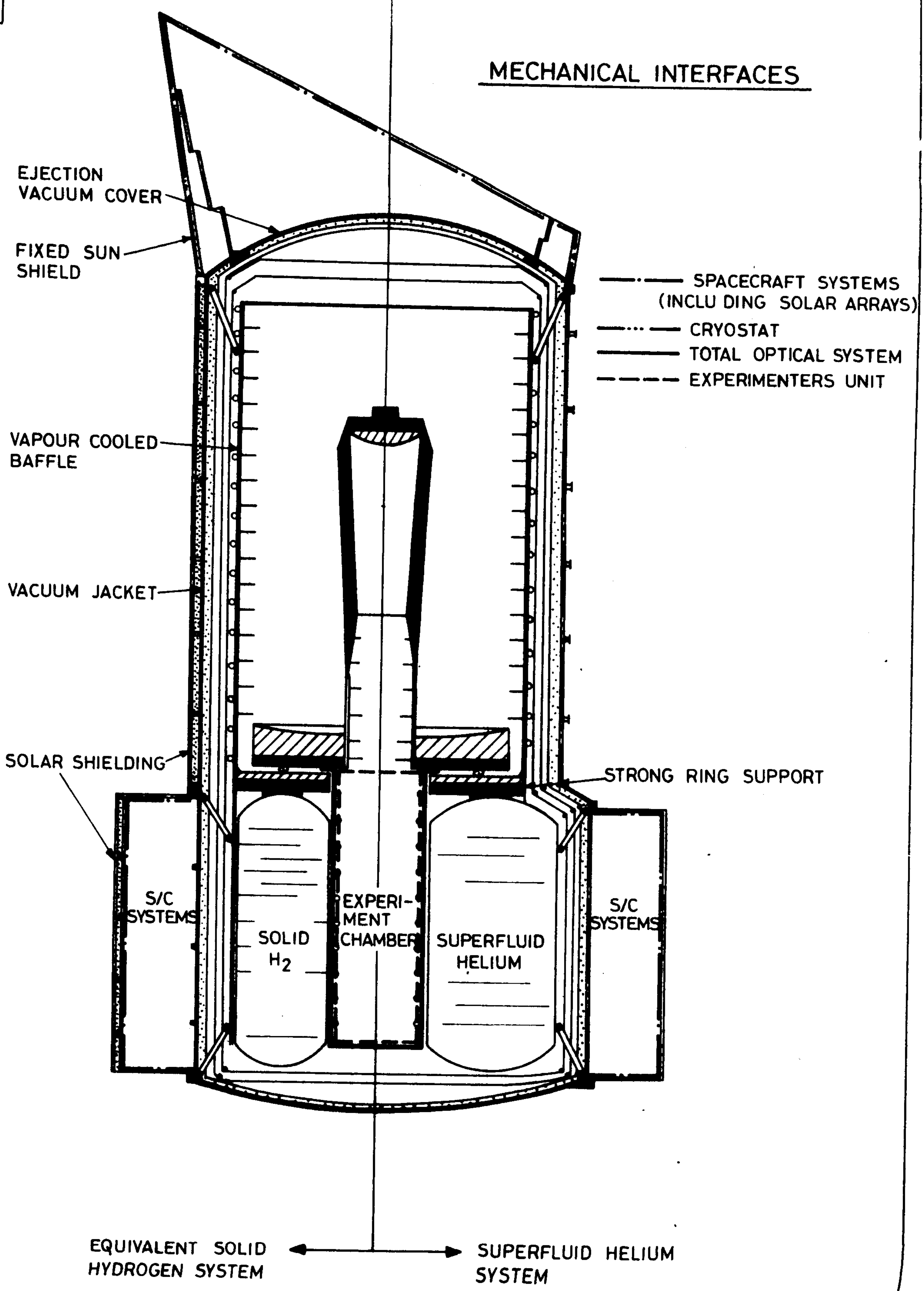

FIGURE 4

On the basis of a 100 cm diameter primary mirror and solid hydrogen as the cryogen, the estimated mass breakdown is as follows:

Pressure Vessel	300	kgm
Cryogen Tank	50	
Vapour Cooled Shields	60	
Supports and Insulation	40	
Plumbing and Valves	30	
Strong Ring	30	
Telescope Mirror	90	
Secondary Optics/Supports/Baffles	60	
Experiment/Supports	50	
Main Telescope Baffle	80	
Sun Shield (fixed)	50	
Ejection Cover	40	
*Solid Hydrogen Cryogen	60	
ELectronics + Cable Harness	80	
S/C Adaptor	50	
S/C Support Structure	60	
Solar Arrays	80	
S/C Subsystems	90	
	1300	kgm

*Use of superlfuid helium as the cryogen would add roughly 250 Kg to this figure.

This can be compared with the total mass for IRAS, which is roughly 1000 kgms, and which has a 60 cm diameter primary and carries 70 kgms of superfluid helium.

5.2. Cryogenic System.

The major uncertainties at this stage in the design of the cryogenic system are the heat inputs via the supports and the aperture. Extrapolating from existing designs for cooled space telescope systems, it appears that by the use of efficient, passively cooled outer baffles it should be feasible to keep the aperture loading down to roughly 30 mW in the astronomy operations. The support structures are likely to inject about 60 mW. Estimating 30 mW input from the electrical wiring, 8 mW from the fill line, 5 mW from the multilayer insulation, 2mW radiation leakage, and 15 mW average from the experiment systems, leads to a total integrated heat dissipation of 150 mW. This is consistent with the quantities of cryogen indicated in Fig. 5 for a 1 year lifetime with a ∿ 25% margin. Of course, this is an extremely crude estimate and a further specialized study is required at an early stage to carry through the iterative process which optimizes the temperature distributions for minimum cryogen losses.

Figure 5 indicates the configuration and masses for the two possible cryogens that have been considered. Clearly solid hydrogen is to be preferred in terms of lower mass and volume (or longer mission lifetime). However the decision between solid hydrogen or superfluid helium rests partly on scientific require-

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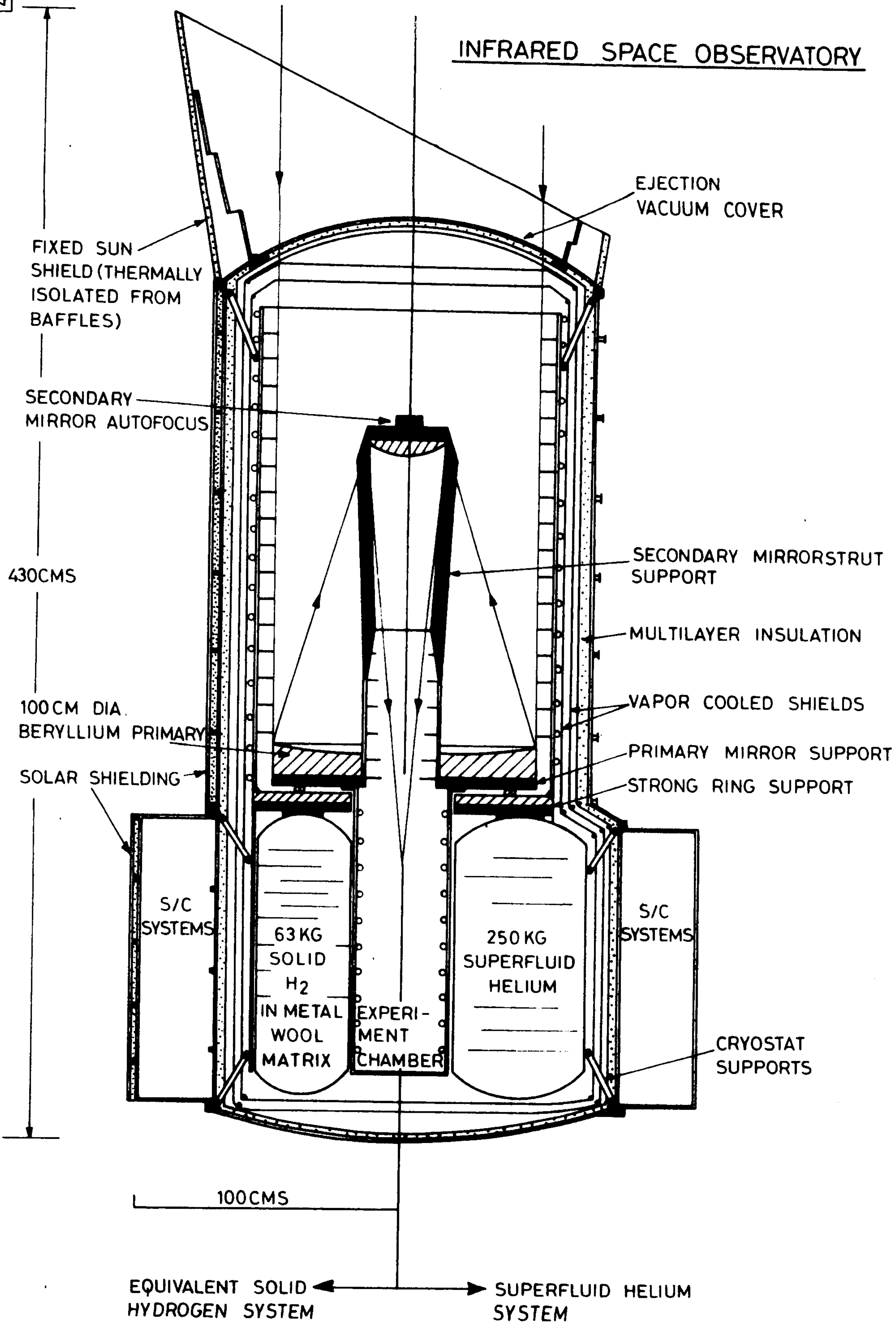
INFRARED SPACE OBSERVATORY



TOTAL MASS 1300 KG

PERMISSIBLE (INTEGRATED) HEAT LOAD, 150 mW OVER 1½ YEARS

FIGURE 5

ments. That is, when photoconductor detectors are used beyond 28μm, they require an operating temperature below 4K, and hence the use of liquid helium. Therefore, the choice of solid hydrogen as the main coolant implies the addition of a helium vessel when the wavelength coverage is extended to 200 μm.

There is in addition a potential technical problem with any solid cryogen. This is the difficulty to provide continuing adequate thermal contact to the cryogen as the solid material is evaporating about the contact points of the metal matrix. Solid cryogen systems have however been flown on spacecraft successfully and presumably this problem can be solved. It remains now to make an early decision in favour of one or other cryogen considering the scientific factors, the technical risks, the trade-off with mission duration and the expertise of European industry with each cryogen.

5.3. Power System.

Power generation by deployable rigid arrays is foreseen. This could be a two panel each side version of the existing ECS array, with a rotation axis perpendicular to the optical axis. Alternatively, an enlarged version of the IUE array could be used.

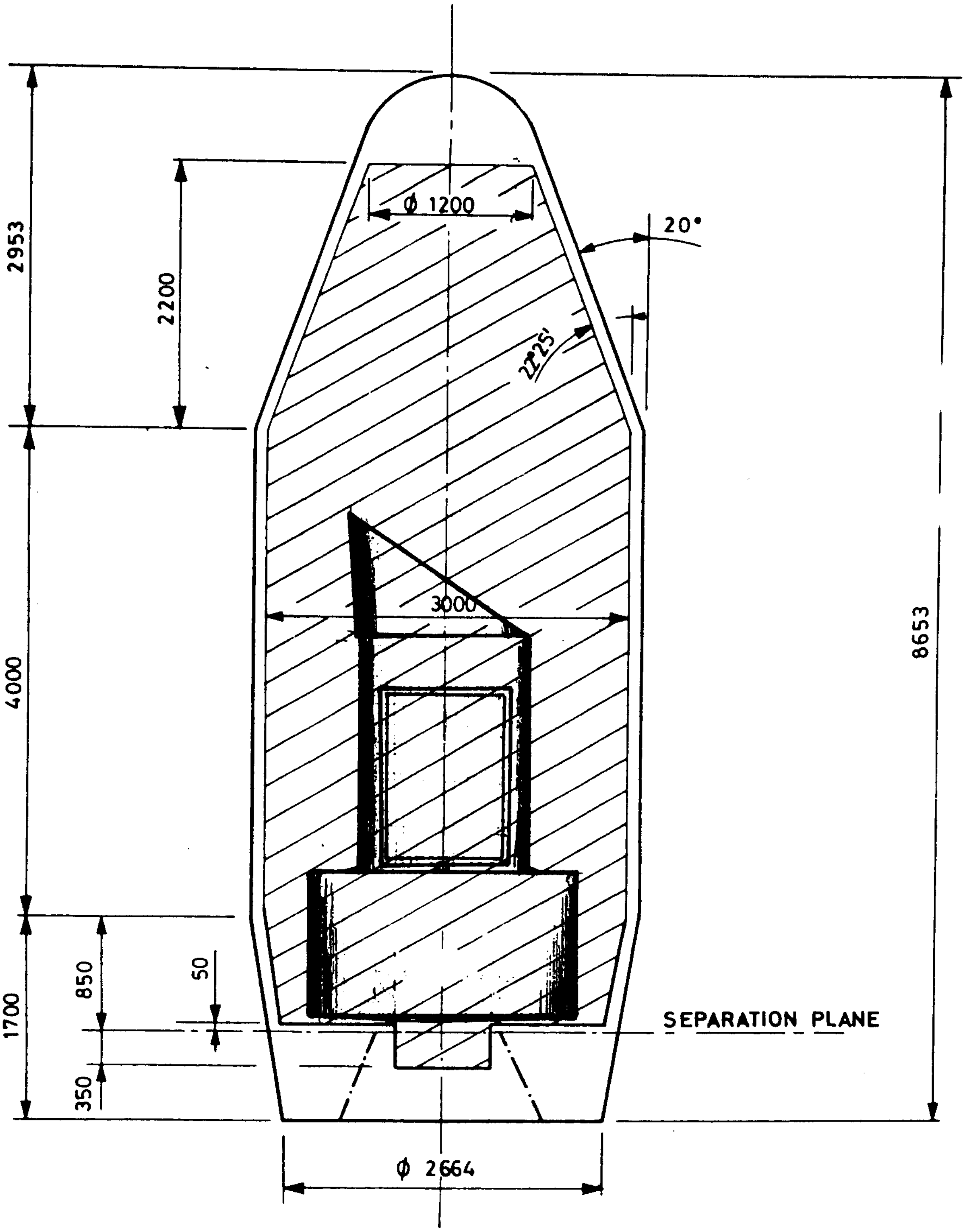
The ECS type array could be capable of delivering roughly 700 Watt average at the start of life. This would be adequate for the foreseen instrument and S/C systems required and probably would cover also the added requirements placed by including a heterodyne detection system. The ECS array in deployed configuration is illustrated in the sketch on the title pages.

5.4. Attitude Determination and Pointing System.

A 3 axis pointing accuracy of 15 arc seconds is called for with a 1 arc-second pointing stability over a period of up to 20 minutes. Various attitude sensors are available for the coarse (∿ ½ degree) attitude measurement. Fine attitude determinations could be achieved by a star mapper or by using the finder telescope in conjunction with an acquisition camera. The system used by IUE, which has proved very successful, could be employed. In this case the primary attitude sensor is an inertial reference assembly (IRA) consisting of six precision single axis rate intergrating gyros. Coordinate transformation and attitude computation is done by an on-board computer. Attitude control torques are provided by a momentum exchange system using three conventional reaction wheels arranged in an orthogonal triad. Momentum dumping would be by helium gas jets for the case of ISO.

The IUE system provides for telescope pointing by astronomers commanding through the ground computer. Pointing stability of the system is 1 arcsecond. Large slews do not retain this accuracy in the IRA, but the resulting position is sufficiently accurate to place the new target in the 30 arcminute field of the finder telescope. The new field can be imaged by the associated acquisition camera and relayed to ground where it is displayed via the ground computer on the T.V. monitor. From the display,coordinate changes are calculated to bring the target into the infrared optical axis and commands are sent for the final slews.

It is foreseen that the relationship between the optical axis of the finder telescope and the infrared axis of the main telescope will be updated frequently using the InSb array camera (4.2.3).



ISO MOUNTED IN THE ARIANE FAIRING.

FIGURE 6

5.5. Launcher and Orbit.

It is assumed that by 1985 Ariane will be available on a routine basis for the launch of European scientific payloads. Information on the projected Ariane performance which is presently available suggests that it will be capable of launching about 1,800 kgms into a geosynchronous orbit or about 1500 kgms into a 10^o inclination orbit with an apogee of $\sim$ 36,000 kms and a perigee of 200 kms. Either of these orbits would be very suitable for infrared astronomy. A geosynchronous orbit would require the addition of an apogee motor at a penalty of about 350 kgms. Despite this, the all-up mass would still be within the Ariane capability. The advantage of such an orbit for astronomy is that of continuous real time control from a single ground station. Not only can operations run 24 hours per day, but in addition the direct involvement of observers permits optimization of observations. Both factors are of vital importance for a mission of limited duration. Unfortunately, the angular resolution of a 1 meter telescope at geosynchronous orbit is not sufficient for atmospheric studies of the earth. Therefore if it is concluded, after further study, that atmospheric studies should be done by this mission it will be neccessary to use the compromise of a highly eccentric orbit. Such an orbit can provide for real time control from one groundstation for much of the orbit above the radiation belts. A second groundstation could however be required if data are taken through perigee. Such a station might be used simply for a data dump. A low orbit is considered to be less attractive for astronomy. The short period and Earth obstruction calls for frequent slewings with considerable loss of efficiency. It is also likely that there will be an additional thermal load on the outer baffles due to the proximity of the Earth to the field of view of the telescope. However Ariane can place 2500 kg in a 700 km sun synch. circular orbit of 98^0 inclination.

5.6. Communications.

Both uplink and downlink communication should be carried out at s-band. This will allow use of the planned ESA s-band tracking network. A basic telemetry rate of 100 K bits/sec is required. Much of this will require processing in real time to provide operational feedback from observers. The requirement will therefor be for a dedicated observations and control unit within a station such as Villafranca. On-board equipment such as the transponder, encoder and decoder should utilize standard ESA sub-systems.

5.7. Data Handling.

The concept of essentially real time operations with a dedicated computer is an attractive one and very efficient. Actual operations would have some similarity with the present IUE operations. The difference would be that ISO will have three to four different instruments, each having dedicated software systems with appropriate operational modes.

Preparation of science instrument operations software and the appropriate data processing software, covering such things as Fourier transforms, calibrations, systematic error corrections, will necessarily be prepared and supplied by the groups providing the scientific instruments. During the 3 months of exclusive use of ISO, the instrument groups will be responsible for providing improvements to each software batch. Similarly, they will be required to participate with ESA personnel in the process of improving operational efficiency during this initial period.

The intention is that observers will be able to obtain quick-look visual data during operations and obtain copies of this to take away on completion of the observing run. Recorded data will also be available at that time. The aim would be to have that data in a form where the basic calibrations and corrections have been carried so that the observer can concentrate on further, more detailed, processing at his home institute.

6. COMPARISON WITH OTHER SYSTEMS.

Other space infrared astronomy systems have been proposed or are in the hardware development phase. Here, we will briefly present their prime characteristics and compare them with the present proposal.

The present proposal is perhaps closest to the proposed SIRTF mission, being studied by NASA. Both the scientific objectives and the proposed focal plane instrument complement are quite similar. The striking difference between the two missions is in the mission duration. This difference is especially important when one considers the effects of the learning curve involved in operating complex scientific instruments in a novel environment. Especaily for an observatory type mission the one to two years foreseen for ISO are extremely important to achieve maximum science benefit (IUE illustrates this point). We believe that the gain associated with the extended duration of the ISO mission offsets any advantage of the Spacelab environment. Obviously, there are many basic scientific reasons to prefer a long duration mission, such as the opportunity to study more objects, to obtain higher sensitivity, to achieve maps to lower surface brightness levels or of larger regions, to study variability, etc.

An interesting comparison can also be made with GIRL. This telescope will carry photometric and spectroscopic instruments. In many respects the GIRL mission will be precurser of ISO and many studies of an exploratory nature in the infrared wavelength domain can be made by GIRL, thus paving the way for more comprehensive studies by the more powerful ISO. GIRL will be most important in directing the research areas in which ISO could be most usefully deployed.

In comparison with LIRTS the major differences with ISO are mission duration, telescope size and telescope temperature. The LIRTS primary aim was to perform high resolution spectroscopy in the far-infrared and to achieve high angular resolution. Very high resolution spectroscopy in the far-infrared does not require a cryogenic telescope, it can best be accomplished by a very large telescope using heterodyne receivers. In comparing the two types of mission, it was decided that a cooled telescope with instrumentation which concentrates on the region below 200μ was to be preferred. It is in this 1-200μ regime that the transitions occur due to vibration and vibration rotation in molecules and solids, where the atomic and ionic fine structure lines occur and where the infrared excesses are observed in galactic sources. It is in this wavelength region also that major improvements are occurring in photoconductor detector performance, giving NEP's of $10^{-17} W\sqrt{Hz}$, which will allow very large increases in sensitivity when coupled with a space cryogenic telescope. Indeed, it is this very fact of improved detectors that led to a reassessment of the value of the LIRTS concept. However provision for some high resolution spectroscopy in the far infraredis considered for ISO using heterodyne receivers after the cryogen has been used. The table below summarizes the status of infrared space astronomy projects.

	TELESCOPE			DURATION	MISSION OBJECTIVES	LAUNCH	STATUS
IRAS	cryogenic	0.6 m	satellite	1 year	sky survey/photometry	1981	approved
GIRL	cryogenic	0.5 m	spacelab	7 days	spectroscopy/photometry	D4(1983)	approved
SIRTF	cryogenic	1.2 m	spacelab	7 days	spectroscopy/photometry	1985	study
LIRTS	uncooled	2.4 m	spacelab	7 days	spectroscopy	?	studied
COBE	cryogenic	0.6 m	satellite	1 year	cosmic background	1985	study
ISO	cryogenic	1 m	satellite	1-2 yrs	spectroscopy/photometry	?	proposal

7. SUPPORT AND RESOURCES OF SCIENTIFIC COMMUNITY.

The scientific community involved in the ISO mission is very broad. From the description of the scientific objectives it is clear that the mission will contribute to the development of a variety of fields in astrophysics and - should the submillimeter system be included - also to atmospheric physics. Such a wide range of applications of an observatory satellite is to be expected and there is no question about the general interest in the astronomical community to support such a mission.

Here we will specifically address the subset of infrared astronomers and their associated hardware teams. The total number of infrared groups in Europe is at least 20, fairly evenly distributed over the ESA member states. Most of these groups are involved in groundbased balloon and or aircraft infrared astronomy. Some of them have experience in building hardware for rocket, satellite or Spacelab projects.

With the advent of IRAS and GIRL the involvement of other European astronomers in infared astronomy will increase considerably.

There is no question about the interest and the ability of European infrared astronomers to participate actively in the development of focal plane instrumentation for ISO. The same holds for involvement in the data reduction and interpretation of the results.

On the front page we have presented a list of those who have either, through participation in discussions leading to this proposal, or in writing supported the idea of a European space observatory mission in infrared astronomy.

8. SCIENCE MANAGEMENT.

The management of a multi-user project like ISO requires a carefully designed structure which is sufficiently flexible to cope with a scientifically oriented users community and yet maintains enough rigidity to keep costs and schedules under control.

The primary concern after project approval is the development of top level system requirements which should directly derive from the scientific objectives of the mission. Already at this stage realistic system level inputs should be available to allow for a meaningful interaction between project complexity and cost, and science objectives. It is imperative that the scientific user community is strongly involved in this stage, as far-reaching decisions are involved which usually cannot be reversed. To aid this process it is suggested that ESA appoint an ISO Science Advisory Group which would include senior representatives of potential users together with interested theoretical astrophysicists. Their brief would be to advise the Agency on important scientific matters in this initial phase of the project design and instrument selection process. They would also be involved in the decisions concerning operations, data handling, and proposal selection procedures.

We propose to arrive at the system requirements through interaction between an ISO Instruments Science Team and a team of system engineers and specialists. THis group is subsequently charged with the development of the necessary requests for quotations from industry for the development of spacecraft hardware, the telescope and the cooling system. The science team should be in a position to critically review and discuss the specification section prior to the submission of the rfq to industry. When such a procedure cannot be implemented strictly, the Science Team should at least be permitted to review the specification immediately after release so that modifications can be agreed upon well before the deadline of proposal submission.

Clearly, before the specification of the telescope and spacecraft can be written the instrument complement must be well defined. This level of definition should be arrived at by the mechanism of an Announcement of Opportunity to the scientific community for participation in the hardware development of focal plane instrumentation and software development for data reduction. It is anticipated that instrument teams will be formed, selected by ESA on the basis of quality of the proposal, competence, experience and the availability of a budget (national or multilateral). This ISO Instrument Science Team selection process should be completed before or just after project approval is obtained. During the project hardware execution phase a close liaison between development of spacecraft hardware, ground support hard- and software, instrument development, operations systems and science users must be maintained. The best way to achieve such a liaison is to have regular project reviews with active participation of the Instrument Science Team. This science participation is especially important in situations were trade-offs need to be made that have a science impact. It is not sufficient to operate solely through a project scientist, although his role for day to day contacts with the project is extremely important. He should be the focal point of interaction of the project with the scientific user community. Important decisions should be brought before the Instrument Science Team and the ISO Science Advisory Group.

The instrument teams need to be under closer surveillance than normal by the ESTEC Project Team, because of the multiple interfaces with the cryogenic system and the telescope. Nonetheless paper work should be reduced to the bare minimum. Rather, intensive contacts by an ESTEC based ISO instrument manager and engineer should exist. During instrument development the interface point between the project and the instrument development should be via the ISO instrument manager, not via the S/C contractors. The instrument manager and instrument engineer should also take an active role in the integration and testing of the telescope assembly and the focal plane instruments and participate in instrument design and development reviews.

During the operational phase of ISO the use of the scientific instruments and data resides exclusively with the instrument development teams for a period of 3 months. After this period ISO should be available to the scientific community. Time allocation should be made through peer group reviews of proposals by a Selection Committee in consultation with the science team to ensure proper use of instruments and spacecraft. The nature of the satellite requires that the time allocations are made before launch; an adjustment of the observing programme shall be made immediately after the initial check-out phase to account for actual on-orbit system performance.

During the operational phase the Science Team is charged with the responsibility to perform scientific instrument performance verification and to provide inputs for updating and fine tuning the science data reduction system. As each instrument has its own data reduction requirements, software for data reduction for all instruments shall be integrated at a central satellite control and data reduction facility. Data products should be readily accessible for scientific analysis by the user community.

The composition of the Science Team consists of representatives (teamleaders) of the instrument and data reduction teams and of one or two additional scientists selected on the basis of the response to an announcement of opportunity to participate in the ISO project. The chairman is appointed by ESA.

Obviously a feasibility and preliminary design study is needed before the project is approved. It should be stressed that the study phase must lead to the identification of instrument teams which will subsequently form the project science team. This ensures both a timely start of instrument development and a timely involvement of scientists in the final satellite definition. ESA has already indicated the way scientists are involved in the study phase and this aspect is therefore ignored in this proposal.

Especially important aspects of the study phase concern the choice of telescope size and cryogen system which are the main cost drivers. Also, the feasibility of inclusion of a submillimeter heterodyne system should be studied in detail and a decision should be reached based on the availability of the technology for heterodyne receivers at very high frequencies and on the acceptability of the added complexity.