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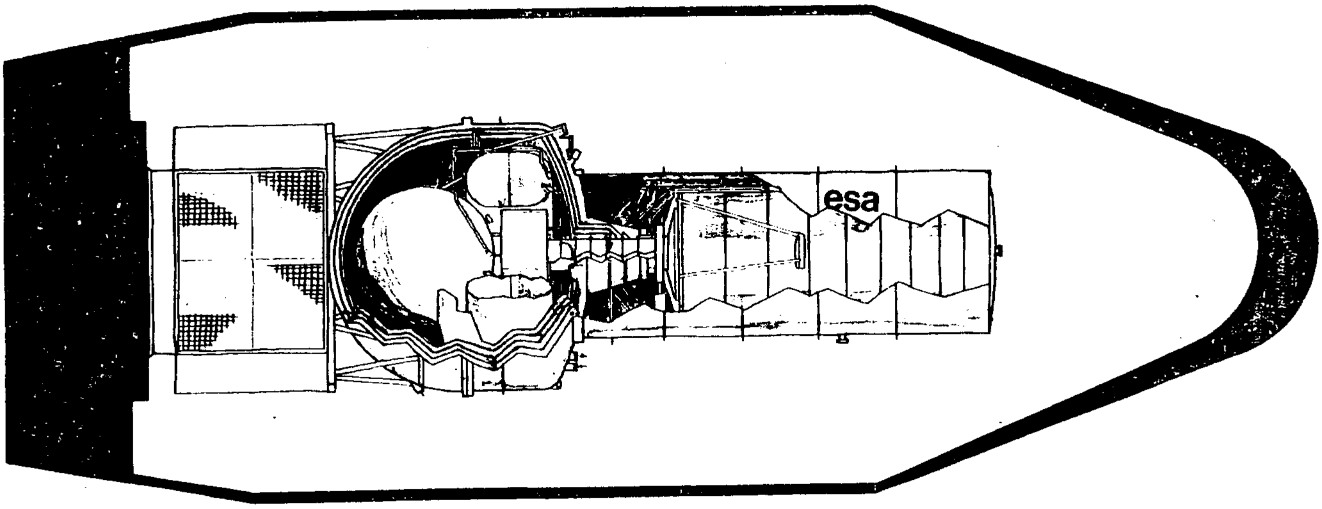
# INFRARED SPACE OBSERVATORY

# (ISO)

## PRE-PHASE A STUDY



## FOREWORD

A proposal for an Infrared Space Observatory (ISO) was submitted to ESA in response to an announcement of a new planning cycle issued in November 1978.

The original proposal, made by van Duinen (NL), Courtin (F), Fitton (ESA), de Graauw (ESA), Harries (UK), Jennings (UK), Künzi (CH), Magun (CH), Moorwood (ESO), Salinari (I) and Wrixon (Eire), called for a 1 m cryogenically cooled telescope containing focal plane instruments for infrared and sub-millimeter heterodyne astronomy and, possibly, atmospheric research.

After evaluation of all the proposals received in response to the above-mentioned announcement, the Astronomy Working Group (AWG) recommended this proposal for an assessment study. This recommendation was subsequently endorsed by the Science Advisory Committee (SAC).

In November 1979, the assessment study of the mission (reported in document SCI(79)6) was presented to the scientific community. Subsequently, the AWG and SAC recommended this mission for further study and, in particular, demonstration of the feasibility of a cryogenic system for long-operation flights. During the first half of 1980, two preliminary industrial studies were performed on two different cryogenic concepts. The results of these two studies were presented at the ISO Workshop, held at ESTEC on 28-29 May 1980.

Parallel to the industrial activities, a more detailed definition of the model payload (focal plane instruments) was undertaken by W. Aalders, I. Furniss, R. Hofmann, R.D. Joseph, D. Lemke, A. Moorwood, R. Papoular, P. Salinari, F. Sybille and J. Wynbergen.

At the same time, the scientific objectives were reviewed by P. Clegg, R.J. van Duinen and T. de Jong, with inputs from H. Habing, M. Penston and P. Swings.

ESA personnel involved in the study included R. Emery, B. Fitton, R. Lainé, J. Lizon-Tati, D. Naylor and H. Olthof.

The present document describes the current baseline concept for further studies on the ISO mission.

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## 1. SUMMARY

The rapid advances made in infrared astronomy in recent years have resulted in major contributions to studies of a diverse range of astrophysical objects. These include observations ranging from extragalactic systems, large scale galactic structure, molecular clouds and star formation regions, HII regions and evolved stars, through to planetary atmospheres and cometary studies. These contributions have been made despite the severe limitations imposed on observations by atmospheric effects and the thermal emission from uncooled optical systems. In order to reduce these limitations, IR telescopes have been used on board aircraft and balloons, but these measures have only partially alleviated the problem. Improvements in IR detectors for $\lambda < 120$ µm lead now to a situation where only by cooling a telescope to around 20 K and placing it outside the Earth's atmosphere can the technological advantages be fully exploited to provide an increase in sensitivity of several orders of magnitude.

The 1980's will see infrared astronomy step across this atmospheric barrier with a number of IR space missions, and the impact of that transition will doubtless be of the same order as was made when UV and X-ray astronomy took that same step. A photometric survey of the IR sky in 4 wavelength bands will be carried out by IRAS, and, covering galactic regions at low spatial resolution, by the Small Infrared Telescope using Spacelab. Some initial spectroscopic studies will be performed from Spacelab using GIRL. ISO is meant to follow up and exploit these earlier measurements with a range of IR observing facilities including high resolution spectroscopy. It will also allow absolute photometry at sensitivities approaching the limit set by the zodiacal light background, at an angular resolution somewhat better than that of GIRL and IRAS. The orbit proposed for ISO will allow integration times of hours to achieve the highest level of sensitivity for selected small regions of sky. The planned ISO mission lifetime of 1½ years will enable it to be used for the study of a whole range of astrophysical objects at an unequalled sensitivity.

ISO consists of a cooled 0.6 m diameter telescope in a 3-axis stabilised spacecraft which can be pointed with 10 arcsec accuracy. The telescope and scientific instruments are cooled by a dual cryogen system involving liquid helium and liquid hydrogen. Studies have shown that the proposed system can provide a 1½ year mission duration with generous margins. The cryostat initially contains 67 kg of superfluid helium to provide a range of temperatures down to 3 K, and 26 kg of liquid hydrogen to provide the bulk of the total cooling which is required for the cryostat vapour cooled shields. A number of instruments can be accommodated, consistent with the concept of an IR astronomy observatory, and a model instrument payload has been studied. This consists of a near-IR imaging camera (1-5 µm), two Michelson interferometers (one covering the wavelength range 2-5 µm and the other 5-25 µm) with spectral resolving powers up to $10^5$, and a four-band photometer (8-115 µm).

The choice of a cryogenic telescope ($T \sim 20^{\circ}K$), in preference to an uncooled telescope, and the decision to concentrate on the wavelength range below 120 µm arises from consideration of three main points : 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 recognition that, in the Space Telescope era, extragalactic studies are likely to have particular prominence; iii) the recent developments in IR photoconductor detector technology which have led to an improvement of at least two orders of magnitude in detector performance for $\lambda < 120$ µm. The situation now is that a space infrared telescope cooled to $T \sim 20$ K and coupled to modern photoconductor detectors will give a sensitivity which is approaching the limit set by the zodiacal light background. This would, for example, mean that for the photometry of normal galaxies, having no IR excess, the photometric sensitivity would be comparable to that of existing optical photographic sky surveys. This enormous gain in sensitivity has occurred at the same time as the development of two dimensional detector arrays which will allow imaging in the near infrared (1-5 µm) at the same high sensitivity.

ISO is planned as an observatory, operating as far as possible in real-time, and is intended to be used in a similar way to IUE by astronomers whose observing proposals have been accepted by an ESA Selection Committee. It will differ from IUE in two respects. First, the scientific payload will be designed and built by national groups. Consequently, an initial period of about 3 months will be required not only for commissioning the spacecraft and instruments, but also to provide an immediate return to those groups who have contributed to this hardware development. Some PI group involvement in operations will also be essential during the remainder of the mission lifetime in order to ensure efficient operation of the instrument and will require a concomitant assignment of observing time. The second difference from IUE is the use of a 12 hour orbit requiring two ground stations, a prime and a slave station.

It follows from the observatory concept for ISO that proposals from the scientific community for its use can be expected to cover a very wide range of scientific subject areas. IUE has clearly illustrated the benefits which accrue from such a concept.

Of the many possible scientific areas where ISO will have an important impact, the field of extragalactic astronomy is expected to be one of particular importance. Estimates of the number of galaxies to be detected by IRAS suggest a figure of at least 40,000. Detailed observation by ISO of a selection of these, particularly involving spectroscopy of the brighter galaxies, will enormously enhance the astrophysical information derived from these detections. The fact that ISO will be able to integrate on weak sources if necessary for extended periods means that it will in practice achieve considerably improved sensitivity, and hence see much further. This will be particularly valuable to such extragalactic observations. The classification, total luminosity and continuum energy distribution measurements, together with mapping of galaxies, will be basic ISO photometric measurements, as will studies of time variations in active galaxies. In the near infrared observations of the CO and $H_2O$ bands can give information on stellar populations in galaxies (and possibly QSO) and provide evidence of evolution as a function of redshift. Apart from these basic observations, more speculative studies are likely, such as the presence of cool low mass stars in haloes around galaxies.

ISO should make significant contributions to cosmology. It may be possible to define infrared galaxies as standard candles for calibrating the distance scale of the Universe. Study of the evolution of infrared properties of galaxies may help to resolve whether the Universe is open or closed. The high sensitivity of ISO will permit deep searches for galaxies forming out of the primeval fluid.

Studies of star formation processes in our own galaxy and in other nearby galaxies are likely to be quite productive. The energy balance of molecular clouds and the shape of the mass spectrum of stars can be investigated on the basis of photometric observations. The processes that trigger star formation, and the role played by density waves, are best studied by detailed photometric mapping of nearby galaxies. Near-infrared spectroscopy will provide information on the gas dynamics of star forming regions allowing the study of collapse, fragmentation and shock fronts. Analysis of recombination lines and forbidden fine-structure lines of the ionised gas in HII regions, ranging from ultra-compact to well-developed, will result in the determination of the ionising fluxes of massive stars, of chemical abundances in the gas and of chemical abundance gradients in our own galaxy and other nearby galaxies. Spectroscopic studies of more evolved objects ranging from cool giant stars and planetary nebulae to globular clusters will contribute significantly to our knowledge of the chemical abundances and the dynamical evolution of these objects.

Clearly, observations with ISO can be expected to make a substantial impact in most fields of astrophysics.

ISO has no directly equivalent mission competitor. IRAS, to be launched in 1982, is designed as a survey system and will spend roughly 60% of its expected 1¼ year lifetime completing a thorough survey of the IR sky. The remainder of the time may be assigned to a pointing mode for detailed photometric work and very low resolution (~20) spectroscopy. A comparable sized IR cryogenic telescope system of 85 cm diameter, designated SIRT-F, is under active study by NASA and a smaller (45 cm) cooled telescope (GIRL) for astrophysics and aeronomy is being developed in Germany. But both of these are very short duration missions, intended for Spacelab flights. GIRL in particular, because of its early flight date, will be an important precursor to a spacecraft observatory, carrying out initial exploratory studies. These factors taken together make ISO a very timely project, particularly when the schedules for complementary facilities such as Space Telescope are also considered.

As already pointed out by the ESA scientific advisory groups, in the 1980's the future of European astronomy must depend mainly on large observatory class satellites if it is to remain competitive. ISO is in this class. The science that can be accomplished with such an observatory is outstanding and its development in Europe will further ensure that Europe remains in the forefront of future astrophysics research.

## 2. INTRODUCTION

The atmosphere of the Earth is opaque through most of the ten octaves of the infrared electromagnetic spectrum from 1 μ to 1 mm wavelength. There are several narrow 'windows' of varying degrees of transparency at the shorter wavelengths, but in general atmospheric absorption and emission place very severe constraints on both the wavelength range and the sensitivity of ground based infrared astronomy measurements. At airplane and balloon altitudes the atmospheric transmission is improved, allowing a greater wavelength coverage. Observations are, however, still limited by the remnant atmosphere, since the dominant noise source arises from the large fluctuations in its thermal emission. Consequently, it is not possible to take full advantage of the new generation of very high sensitivity IR photoconductor detectors which are becoming available for wavelengths less than ~150 μ.

The crucial step into space, which removes the restrictions imposed by the atmosphere, will be taken first by IRAS, which will be launched into orbit in 1982. This mission will provide a 4 channel survey of the IR sky at a sensitivity level comparable to that obtained in the radio regime. This improvement by several orders of magnitude in sensitivity over present IR observations depends first on removing the effects of the atmosphere, but it also requires the cooling of the telescope and the instruments. The cooling reduces the thermal emission from the optics system, which is the other main noise source, thereby allowing observations to be carried out under essentially detector-noise-limited conditions with the high sensitivity detectors. ISO is proposed to follow IRAS in exploiting the space environment for IR observations and so will also use a cooled telescope with cooled instruments. The main purpose for ISO, however, is to provide spectroscopic studies of sources which have been identified to be of interest from photometric measurements. An important facility will also be to make detailed photometric studies of small areas of sky, using long integration times to achieve the highest levels of sensitivity.

Another way of looking at this gain in sensitivity is in terms of observation times, as illustrated in Figure 2.1. The integration times required to reach a signal-to-noise ratio of 10 on a source of a given flux density, for photometry at 5 μm, are compared for a 4 m ground-based (warm) telescope, which is background limited, and a 60 cm cooled telescope in space with the advanced detectors as proposed for ISO. We see that it would require 5 hours to achieve the required S/N for a weak source of 1 mJy using a large ground-based telescope; in fact, atmospheric fluctuations will increase the integration time considerably. A small cooled space telescope on the other hand can achieve this in thirty seconds. It is clear that ISO has a similar advantage over a 1 m balloon telescope at a wavelength of 100 um. For most spectroscopic observations, a similar advantage applies. Moreover, the available wavelength range is unencumbered by the atmosphere.

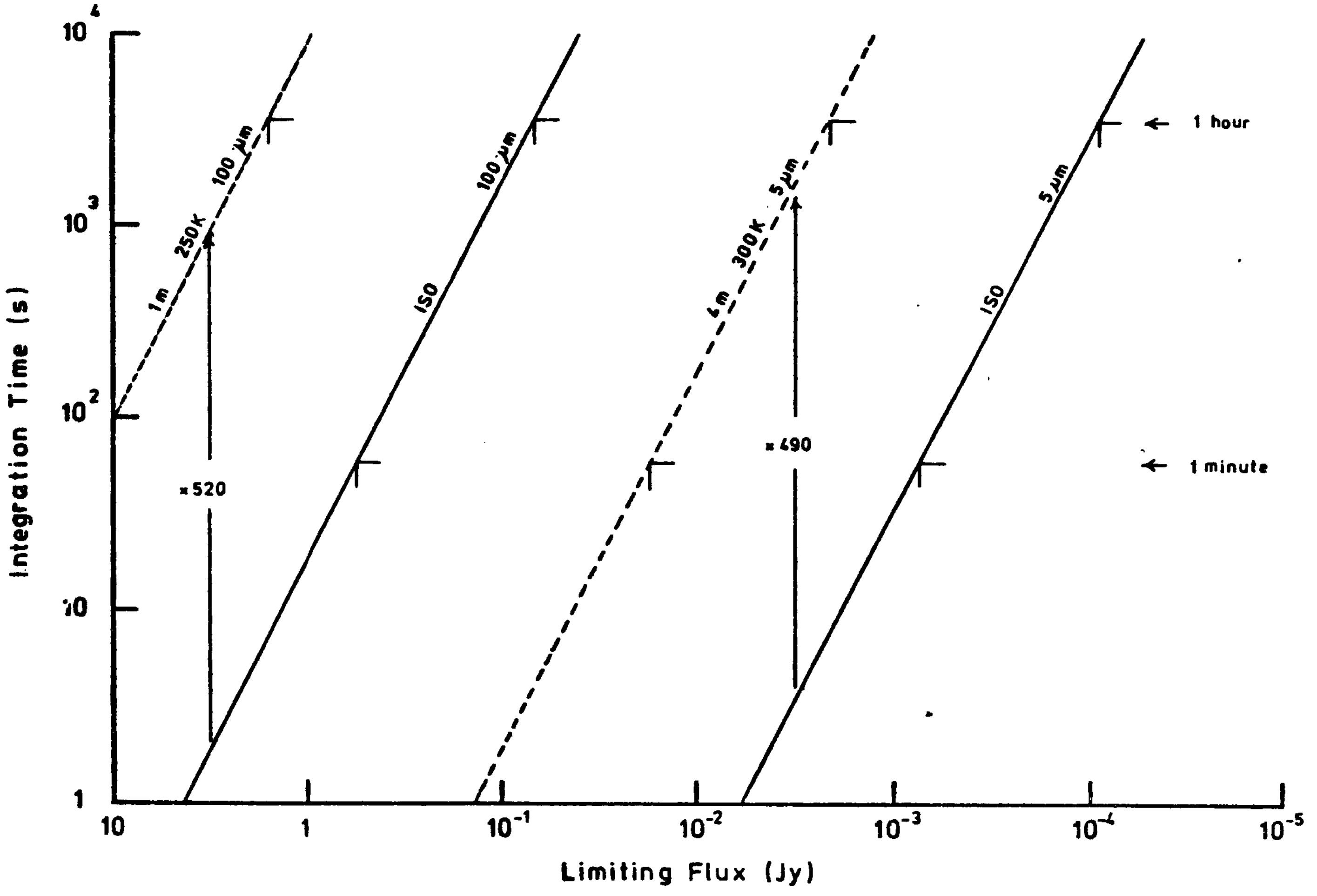

Fig. 2.1 The advantage of ISO over ground-based and balloon-borne telescopes. The integration time needed to obtain a signal-to-noise ratio of 10 on a source of given flux is shown for the various instruments. The performance of ISO at a wavelength of 100 µm is compared with that of a 1 m diameter balloon-borne telescope at a temperature of 250 K, and at 5 µm with a 4 m ground-based telescope at a temperature of 300 K. The factor of improvement achieved by ISO is shown.

Clearly, the ISO mission provides the basis for a major advance for infrared astronomical spectroscopy and photometry, not only by eliminating the restrictions caused by the Earth's atmosphere, but also through the vast gain in sensitivity/bandwidth that a cooled telescope makes possible.

## 2.1 The Instruments

The instrument complement should reflect the scientific objectives of the mission. ISO is primarily conceived as an observatory, so that a broad range of instrument characteristics should be covered. An attempt to group the scientific objectives according to the type of measurement required may be found in Table 2.1. The main wavelength range of interest is indicated, together with the spectral resolution required, classified as low ($\lambda/\Delta\lambda$ = 1 to 10), medium ($\lambda/\Delta\lambda$ = 10 to 100) or high ($\lambda/\Delta\lambda > 100$).

Table 2.1 - Some Important Astrophysical Measurements in the Infrared

| Physical Process | Approximate Wavelength Range (Microns) | Spectral Resolution | Special Interest |
|---|---|---|---|
| Thermal emission | 5-500 | Low | Total infrared luminosity<br>Reradiation by dust in obscured regions<br>Mapping star formation regions |
| Molecular transitions | Vib. 1-25<br>Rot. 15-500 | Medium<br>High | Stellar populations<br>Molecular clouds and dynamics |
| Recombination lines<br>Atomic and ionic fine structure lines | 1-6<br>1-300 | High | Constituents and dynamics of nebulae, etc. |
| ? | 2-300 | Low | Infrared 'active' galaxies |
| Solid state transitions | 2-30 | Medium | Interstellar dust/grains |

Table 2.2 - Model Instrument Payload

| Instrument | Camera Array | Spectrometer | Photometer |
|---|---|---|---|
| Type | InSb 32x32 CID Array | Rapid Scan Michelson Interferometer | Si and Ge photo-detectors with band-pass filters |
| Wavelength Range | 1-5 microns | 2-25 microns covered by 2 interferometers<br>2-5 microns and 5-25 microns | 8-115 microns |
| Resolving Power $\lambda/\Delta\lambda$ | Set of narrow band filters or continuously variable filter | $10^2$-$10^5$ | 3 or 4 bands in the range |
| Telescope Operating Mode | Fixed pointing<br>Offset to a matrix of points | Fixed pointing and offset to a matrix of points | Fixed pointing and raster scan |
| Special Application | Monitor infrared axis of telescope | | Absolute flux measurements |

The model focal plane instrument complement is summarised in Table 2.2. Three basic instruments are needed to cover the range of observations required. A camera array operating in the 1 to 5 µm range will be used for imaging; it also serves to align the telescope optical axis with the attitude control sensors. Spectroscopy in the 2 to 25 µm range is based on the use of two Michelson interferometers, which have the advantage of continuously variable resolution and high efficiency.

Photometry and possibly polarimetry in the 8-120 µm range is the realm of the third instrument, which employs multiple detectors to allow efficient mapping of extended sources. Detailed descriptions of the instruments may be found in chapter 4.

It should be emphasised that this instrument complement is a model payload which was used to assess the feasibility of the observatory type mission. The actual instrument complement may differ somewhat from the one described here.

## 2.2 The Timing of the Mission

While the breakthrough in sensitivity demonstrates the technical advantages of an infrared space observatory, the timeliness of such a mission is also very important.

In the past few years, infrared astronomy has proven its scientific potential in many fields in astrophysics. These achievements have been obtained through the deployment of rather modest instruments in aircraft and balloon gondola. In the early 1980's, the first infrared space missions will be launched, which are of an exploratory nature. For the first time the full potential of cryogenic telescopes in space will be applied to observations in the infrared. The next step which is needed in the development of infrared astronomy is an observatory type space mission : ISO. Scientifically, it is clear that infrared observations will play a critical role in studies of active galaxies, and of star-fprmation regions in our own galaxy. In the scientific objectives outlined in section 3, a selection is presented of some types of observations and astrophysics likely to be accomplished with ISO. Technically, infrared astronomy has also reached a level of development that warrants investment in such a mission. As discussed earlier, IR detector sensitivity has recently improved by more than two orders of magnitude, so that for ISO the system noise would be very nearly equal to the fundamental limit set by the photon shot noise in the thermal emission of zodiacal dust particles. Similarly, infrared spectroscopic techniques, of which Fourier transform spectroscopy is probably the most important, are now well understood and in routine and widespread use.

The timing of an infrared space observatory mission in the mid-1980's is also ideal in the context of space astronomy in general. With the launch of IRAS providing the first high sensitivity infrared all-sky survey, the next infrared space mission needed will be one to follow up with a detailed study of the host of new objects discovered. Clearly, it should have a sensitivity and angular resolution, at least equal to IRAS and it must also be provided with a complement of instrumentation designed for these more refined studies. ISO meets these requirements. Two other space infrared projects are in the planning (SIRT-F) or development (GIRL) phase. Both of these use a cryogenic telescope of a size similar to that of ISO, but they will be flown on Spacelab and are limited to flight durations of 7 to 30 days. The 1½ year mission of ISO has the enormous advantage that it will allow adequate time to fully utilise the gains that the space environment offers to observations in this wavelength range. The timing of the proposed ISO mission, its duration, its instrumentation complement and the observatory concept have each been considered with due cognizance of the Space Telescope era. The ST observations will undoubtedly have a significant bias towards extragalactic objects and this fact is reflected in the wavelength range of ISO, where spectroscopy of highly red-shifted lines in the short wavelength range and photometry at high sensitivity in the 100 µm region are foreseen as important complementary measurements to the ST observations.

## 3. SCIENTIFIC OBJECTIVES

In designing a new instrument and in exploring its future possibilities, one usually aims at solving certain scientific problems. Those problems are defined by the state of knowledge at the time; some will have been resolved and others will have arisen when the new instrument is finally operational.

Infrared astronomy has made a major impact on the study of extragalactic objects and to our ability to observe the elusive locations of star formation in the galaxy. Yet, these discoveries have been made with infrared astronomy still confined to the use of modest instruments on aircraft, baloon gondolas and ground-based telescopes, all suffering from the presence of the atmosphere. The step into space, permitting the use of cooled telescopes of unprecedented sensitivity, will no doubt give rise to the observations of a whole range of new phenomena.

In what follows, the main emphasis will be on those areas of infrared astronomy that have already proven to be extremely fruitful. We have avoided extensive speculation about new classes of objects and phenomena that may very well be within the horizon of the extremely sensitive cooled space infrared telescopes.

### 3.1 Galaxies and Cosmology

The most distant recognisable object in the universe, the QSO OQ172, has a redshift of $z = 3.53$. On the other hand, primordial photons from the big bang last interacted with matter at $z \sim 10^3$. Between epochs $\sim 10^5$ years and $\sim 10^9$ years there are, therefore, no direct observations of what has happened in the universe. Yet much must have happened. The high degree of isotropy of the microwave background radiation shows that little structure can have developed by the time of recombination but, by $z \sim 3$, we have well defined, compact objects emitting copious radiation. Between these epochs, the whole drama of galaxy formation and the development of large-scale structure in the universe has taken place unobserved.

Even for redshifts lower than $\sim 3$, our knowledge of the universe as a whole leaves much to be desired. The fundamental rate of expansion of the universe is still uncertain by a factor of perhaps two, whilst estimates of the gravitational retardation of that expansion encompass almost all possibilities from a closed, and ultimately recontracting, universe on the one hand to an accelerating universe on the other. Little, too, is known about the evolution of galaxies and galaxy-like objects between $z \sim 3$ and the present epoch and there are many unanswered questions about relatively nearby and therefore contemporaneous galaxies. Especially important are the problems connected with the energetics of active galaxies and the relationship of these objects to so-called normal galaxies.

In these areas, ISO is likely to make significant contributions to our understanding and some of these possible contributions are discussed in more detail below. Two important points should be borne in mind. First, ISO will follow the complete sky survey to be made by the infrared astronomy satellite IRAS. Much of the work of ISO will undoubtedly be the pursuit and detailed investigation of IRAS discoveries. Secondly, ISO will be contemporary with the Space Telescope and it is natural to assume that observations with these two instruments will be complementary.

Any speculation about the contribution of ISO is naturally constrained and conditioned by our present knowledge and understanding. All previous experience has shown that the most exciting results of new techniques in astronomy have been unforeseen; ISO should prove no exception.

## The Study of Extragalactic Objects

Perhaps the single most important result to emerge from infrared astronomy to date is the discovery that many different types of galaxy are powerful infrared sources. In many sources, including our own Galactic Centre, the infrared radiation dominates the power emitted at all other wavelengths. However, difficulties in observing from the ground longward of about 10 µm have prevented generalisation of this result to most objects. The spectra of some sources are shown in Figure 3.1. Clearly, in many cases the spectrum must turn over between 100 µm and 1000 µm to meet the observed radio spectrum, indicating the presence of a large infrared excess. In many galaxies the infrared emission is attributable to thermal reradiation of stellar photons by dust, but in other cases, particularly quasars and BL Lac objects, non-thermal synchrotron radiation is the only likely mechanism. Bursts of star formation seem adequate to explain thermal infrared emission from many galaxies, but the source of energy for the non-thermal radiation is still a mystery.

## Normal Galaxies

ISO can be used to extend, to nearby galaxies, those studies of stars, star formation and the interstellar medium discussed in other sections. Although long infrared wavelengths are practically unimpeded by interstellar absorption, solid state transitions in dust do occur (e.g. the 10 µm 'silicate' and 3 µm 'ice' features). It will be intriguing to see if the strength of these depends on type of galaxy or the presence of non-thermal sources since this may enhance our understanding of dust composition and formation or destruction processes.

In general, of course, ISO will be most sensitive to the presence of the coolest stars. Because the Hayashi effect funnels evolved stars into the M giant part of the Hertzsprung-Russell diagram, these therefore are the ones seen best. These stars contain strong molecular bands of CO at 4.6 µm and $H_2O$ at 2.0 µm which can be used for population studies and to search for evolutionary effects. These bands will also be extremely powerful probes of the presence of stars in QSO's.

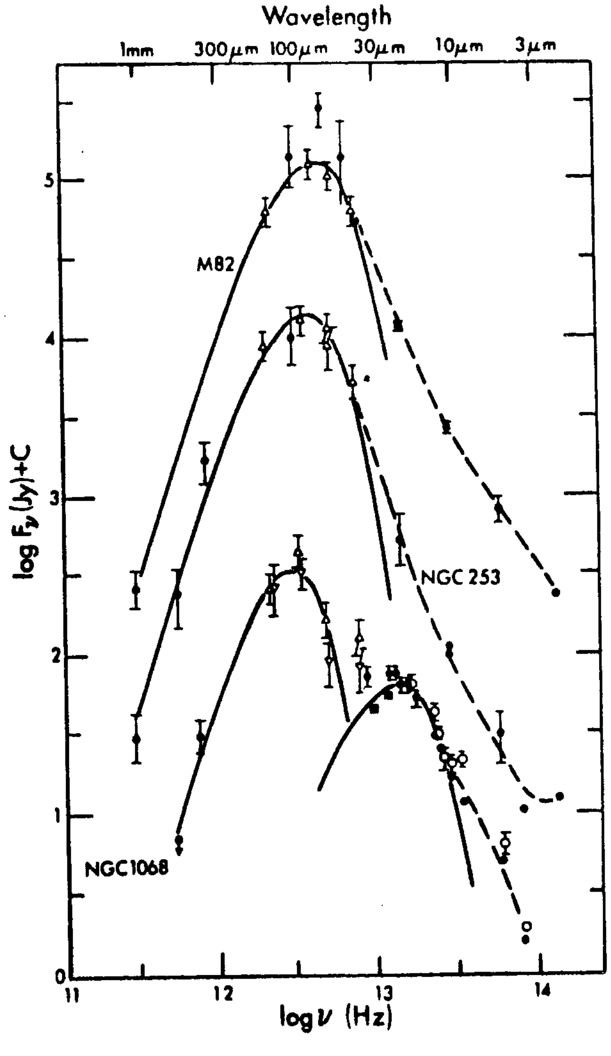

Fig. 3.1 Spectral energy distributions of the central regions of three active galaxies, M 82, NGC 253 and NGC 1068. Because of its enhanced sensitivity, ISO can detect many thousands of such galaxies. Extensive infrared photometry of these galaxies will significantly increase our knowledge of processes causing the infrared excess and the rate at which galaxies go through these phases of enhanced activity.

(From Telesco and Harper, Astrophys. J. 235, 392, 1980)

One interesting and particular problem which ISO will immediately solve is the question of whether the 'isolated extragalactic H II regions' - dwarf galaxies containing hot stars - are young, in which case there will be few red giants, or 'rejuvenated' in which many more evolved stars should be present.

A more speculative project for ISO is to attempt the detection of massive galactic haloes, composed of low-mass cool dwarf stars, which have been postulated by theorists from time to time to account for the so-called 'missing mass' in galaxies.

## Active Galaxies

We may anticipate that, by the time ISO flies, many more galaxies with strong infrared excesses will have been discovered as a result of the IRAS mission. However, ISO will have a vital role here in refining the positions of the IRAS sources to secure identifications with optical, radio and X-ray sources. An extremely important recent result is the use of infrared techniques to identify radio sources too faint to be seen on optical plates. These sources are taken to be either galaxies with redshifts $z \sim 1$ or, if they vary, objects like BL Lacertae with very steep spectra. Obviously, ISO, in conjunction with Space Telescope, has a role in probing the natures of these objects and any new types of source discovered by IRAS.

We have already referred to the importance of establishing whether the emission mechanism for the infrared excess is non-thermal or is reradiation by dust. There are two powerful ways to make the distinction. The first is by searching for time variations, in broad photometric bands, in spectra and in polarisation. This is excellently suited to the 'observatory' nature of ISO which allows access to a large part of the celestial sphere at any time and hence permits repeated observations. Secondly, detecting non-thermal emission by measuring polarisations with high accuracy longward of $\sim 10$ µm also demands a cooled telescope, which would be provided by ISO alone.

Spectroscopy too is vital (see Figure 3.2). ISO will have the ability to probe the environment of galactic nuclei by measuring emission and absorption lines. Emission line profiles and intensities provide the usual diagnostic information, particularly in conjunction with optical and ultraviolet data, to determine densities and temperatures by the methods of nebular astrophysics. The greater transparency of dust in the infrared may also allow this type of investigation for galactic nuclei, like that of Centaurus A, which are hidden in the optical. A particular problem, for which ISO observations may be important, is a resolution of the problem set by the anomalous $L\alpha/H\beta$ recombination ratio in quasars and Seyfert nuclei; other hydrogen line series are accessible in the infrared and line intensities for these must be important to understand all details of this effect. Similarly the presence of molecular lines in either emission or absorption can be investigated only in the infrared. Of the

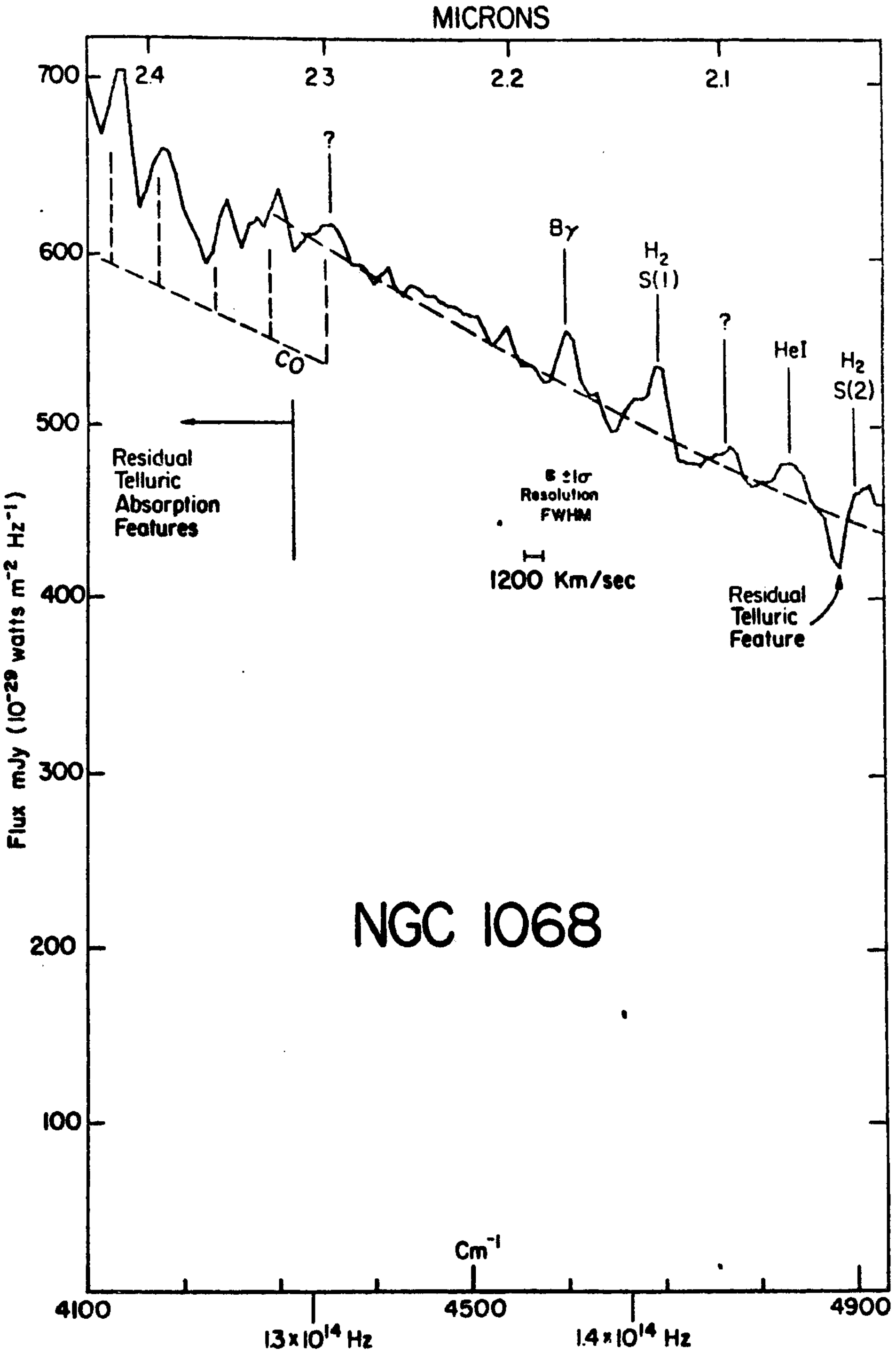

**Fig. 3.2** Near-infrared spectrum of the active galaxy NGC 1068, at a resolution $\lambda/\Delta\lambda \simeq 250$, showing emission lines of ionized hydrogen and helium and of molecular hydrogen. Several unidentified features are also indicated. The enhanced sensitivity and spectral resolution of ISO will allow the study of many more such galaxies in much greater detail.

(From Thompson, Lebofsky and Rieke, Astrophys. J. (Letters) 222, L. 49, 1978) brightest galactic nuclei in the infrared, several, including NGC 4151, Mk 231, IC 4329A and NGC 7582, have optical nuclear absorption lines. The probability that solid state or molecular absorption lines, arising in the same regions, can be seen by ISO is good and would lead to a new grasp of the composition of nuclei in active galaxies.

## Cosmological Studies

The distinction between studies of galaxies on the one hand and of cosmology on the other is, of course, somewhat artificial. Galaxies are the probes of the large-scale structure and evolution of the universe; the farther out we can study galaxies, the larger structure we can study and the longer the role of history available to us. Figure 3.3 shows the region of luminosity-redshift space available to ISO, that is the redshift out to which we can observe an object of given luminosity.

In the Figure are shown some well-known sources, both at their actual redshift and at the maximum redshift at which ISO could see them. At very large redshifts an object has to be rather luminous to be accessible, but, as discussed below, rather high luminosities might be expected.

The ISO photometer field of view in all three channels is the diffraction limit at $\sim 100$ µm, that is $\sim 80''$. Even for $\Omega$ as high as unity, this field of view implies a linear diameter of not less than 100 kpc for all values of z between 0.1 and 30. Protogalaxies will therefore appear as essentially point sources to ISO. Typical galaxies will, on the other hand, begin to be resolved at distances $\lesssim 50$ Mpc.

We may expect ISO to answer questions in several different areas.

## Classical Cosmological Tests

The Hubble parameter $H_0$ and the deceleration parameter $q_0$ are of fundamental importance for our knowledge of the structure of the universe. That they are relatively poorly known is a result of two coupled problems of interpretation. First, all methods of determination depend upon interpreting the appearance of an object in terms of its assumed intrinsic properties; various assumptions lead to estimates differing by a factor of $\sim 2$. Secondly, to reduce scatter arising from the proper velocities of objects, observations have to be pursued to large distances and consequently to earlier epochs. Unfortunately, intrinsic properties of galaxies are likely to change with epoch, making interpretation difficult.

It is known that the width of a galaxy's HI line and its optical luminosity are correlated. A somewhat tighter correlation is obtained between the line width and intrinsic infrared luminosity, mainly as a result of lower and less uncertain reddening within the galaxy. This has recently been used to suggest a revision of the value of $H_0$. ISO

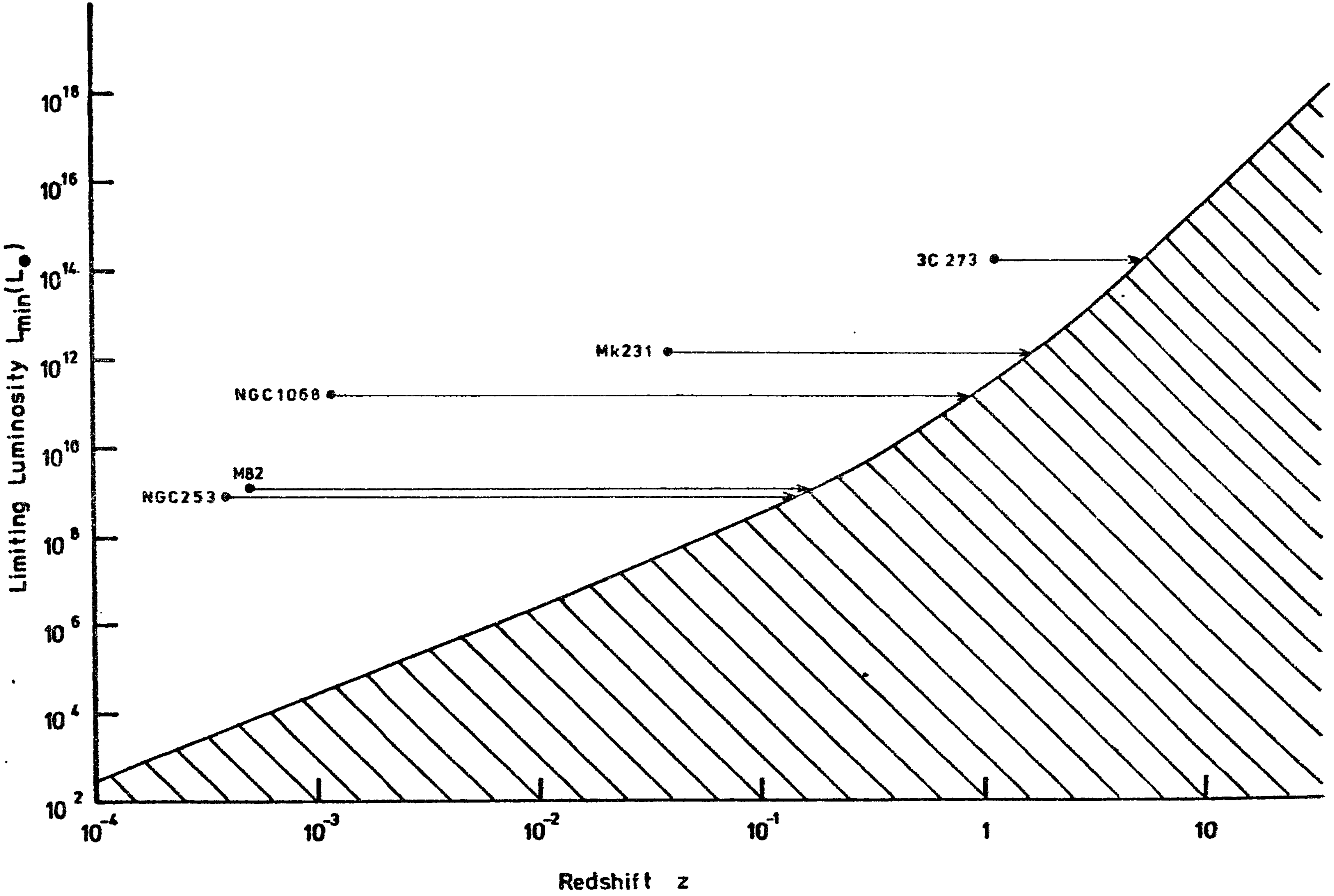

Fig. 3.3 The region (unhatched) of luminosity-redshift space available to ISO. The limiting luminosity (characterised by $\nu L(\nu)$, where $L(\nu)$ is the spectral luminosity at frequency $\nu$) is defined as that luminosity which would be detectable by ISO with a signal-to-noise ratio of 10 in an integration time of 1 hour as a function of redshift. $H_0$ has been taken to be 50 km $s^{-1}$ $Mpc^{-1}$ and $\Omega$ to be 0.1. Some well-known objects are also shown, at their actual redshifts, with an arrow showing the redshift to which they could be pursued by ISO: NGC 253 (spiral galaxy), M 82 (infrared galaxy), NGC 1068 (Seyfert 2 galaxy), Km 231 (Seyfert 1 galaxy) and 3C273 (quasar).

may extend this method both by obtaining more precise photometry of a larger number of galaxies and by investigating the correlation over a wider wavelength range. More speculatively, it may be hoped that other correlations may be established between far-infrared luminosities and other properties, perhaps in more intrinsically bright objects such as Seyfert galaxies, enabling analogous methods to be extended to much greater distances.

The history of the universe is a function of the deceleration parameter $q_0$ as well as of $H_0$. As mentioned earlier, ISO can study stellar populations in different types of galaxy, giving important clues to the epochs and timescales of star-formation. This information, as a function of redshift, can then be used to constrain the value of $q_0$.

## The Early Universe

One of the most intriguing problems in cosmology is the origin and evolution of structure in the universe and it is perhaps here that ISO may make its greatest contribution. Any model of the various processes involved must stand up to confrontation with, among other things, the observed homogeneity of the microwave background radiation, the existence of galaxies at very least out to $z \sim 1$, and the observed clustering of galaxies on various scales. The first step should certainly be the search for young galaxies.

Condensations in the universal fluid are unlikely to be detectable until their density constrast with the background fluid becomes of the order of unity and a number of lines of argument suggest that, for galaxy-sized condensations, this occurred sometime between $z = 30$ and $z = 3$. At what point a protogalaxy becomes visible, and what its appearance is at that stage has been the subject of several speculations. A $10^{11}\ M_\odot$ object may achieve a luminosity of $\sim 10^{12}\ L_\odot$ during a brief period of concentrated stellar ignition, but such luminosity is undetectable by ISO at $z \gtrsim 1.5$ (cf. Figure 3.3).

At the other extreme, one may imagine a purely infrared object, such as might be formed from the gravitational collapse of a cloud of gas contaminated with dust from an early generation of 'Population III' stars. Such collapse of $10^{11}\ M_\odot$, containing a fraction $\sim 10^{-8}$ to $10^{-9}$ by mass of dust, can easily produce a luminosity detectable by both IRAS and ISO out to redshifts of 10. One can therefore envisage ISO studying protogalaxies discovered on deep IRAS 'plates'. In particular, evidence of evolution may be obtained by performing number-counts of these objects.

Ideas about the development of structure, on the scale of galaxies and larger, range from fragmentation of large masses emerging from recombination to the sequential growth of larger and larger structure by gravitational processes. If primitive galaxies turn out to be prominent infrared objects, study by ISO of their positional correlations may give important clues towards the solution of these problems.

## 3.2 Star Formation

Although star formation has been a subject of considerable theoretical interest for many years, it has only been since the relatively recent advent of radio and infrared astronomies that a substantial body of observations could be assembled to confront theoretical ideas. As a result, a host of new and fundamental questions has appeared, and concurrently, we have also become aware of a variety of fascinating new astronomical objects, such as molecular clouds, maser sources and cocoon stars. Infrared observations have already proved to be extremely powerful in the study of these dense complexes of dust and gas, and observations using ISO can play a central role in enlarging our understanding of the many facets of astrophysics associated with star-forming regions.

### Star Formation in Molecular Clouds

The observations available so far suggest that star formation takes place almost exclusively in molecular clouds where the gas density is sufficiently high and the temperature is sufficiently low to allow the gravitational collapse of fragments of stellar mass. The details of the fragmentation process are, however, still poorly understood. For instance, the mass spectrum of stars at birth is virtually unknown. Do stars of all masses form simultaneously? Or are low-mass stars formed continuously in a quiescent way in molecular clouds while massive stars are formed only occasionally, possibly triggered by compression of the cloud? What are the compression mechanisms and what is their relative importance? Are spiral density waves the only way to induce star formation or do shock fronts from expanding H II regions or supernova explosions also play an important role? To study these questions, photometric mapping of molecular clouds is needed. This requires rapid - and therefore very sensitive - source detection so that areas typically of about 100 square arc minutes may be mapped reasonably quickly with diffraction-limited angular resolution. This requirement makes it essential to use a cooled telescope in space, such as IRAS and ISO. The IRAS mission has an exploratory and a survey character, while ISO is ideally suited to follow up the IRAS results in detailed photometric studies of star-forming regions.

Sensitive broad-band photometry of star formation regions will provide information on the overall energetics of molecular clouds and will allow identification of the most luminous newly formed stars and their contribution to the total heating of the clouds. Because heavy stars produce much more luminosity per unit mass than low-mass stars ($L \propto M^3$) the energetics of molecular clouds is dominated by heavy stars ($M \gtrsim 10\ M_\odot$) in spite of the fact that many more lower mass stars are born simultaneously. The mass spectrum of stars at birth can be studied with the near-IR camera which due to its good spatial resolution allows the observation of the spatial distribution of less luminous stars (clusters) with masses in the range of 1 to 10 solar masses in nearby molecular clouds.

If ISO were to have the capability of observing the linear polarisation of infrared sources one could attempt to derive the strength of the magnetic field in clouds from infrared polarisation data. Deviations of source geometry from spherical symmetry such as in rotating disks of gas and dust around recently formed stars also lead to polarisation of infrared radiation.

The coming of age of astronomical near-infrared spectroscopy in recent years has opened new and exciting possibilities of studying gas dynamical processes in star formation regions. The discovery of widespread emission around 2 µm in vibration-rotation lines of $H_2$ has demonstrated the presence of hot $H_2$ molecules ($T \sim 1000$ K) in shocks which are probably caused by the interaction of strong stellar winds from newly-formed stars with the surrounding molecular cloud. This picture of stellar winds blowing holes in molecular clouds is supported by observations of highly excited pure rotational lines of $H_2$ and CO at wavelengths in the range from 5 to 150 µm. Expansion velocities in the range 10 to 200 $kms^{-1}$ are observed.

When newly-formed massive stars are still embedded in their dust cocoons observations of near IR Hydrogen recombination lines (Brackett and Pfund series) allow a determination of the electron density and the size of the ultracompact H II region inside the cocoon. The extinction in the cocoon can be derived from the line rations.

The molecular gas can also be probed by observing near-infrared vibration-rotation lines in absorption against the proto stellar continuum. Lines of CO have been observed in this way (see Figure 3.4). The motion, expansion or inflow of the gas can be studied on the basis of the observed radial velocities. Vibrational and rotational temperatures can be determined allowing conclusions about the origin of the molecular excitation. Spectroscopic observations of lines from molecules containing isotopic substitutions both in emission and in absorption provide clues about the chemical enrichment history of the gas (f.i. $^{12}C/^{13}C$, $^{16}O/^{18}O$).

Used with maximum possible spectral resolution the ISO Michelson interferometer is very well suited to observe and map strong lines in distant molecular clouds with embedded OB stars and to detect weak lines in the nearest clouds. These observations will provide extremely important (and hitherto unattainable) information of pre-main sequence evolution of massive young stars and on the evolution of molecular clouds into OB associations.

Pre-main sequence stars, such as T Tauri stars and Herbig-Haro objects all show excess infrared emission at wavelengths beyond one micron. In addition there is a significant number of young stars of all masses associated with arcs, rings and fans of nebulosity that are known to emit infrared radiation. Photometric, spectroscopic and polarimetric observations with ISO will help to better understand these interesting objects.

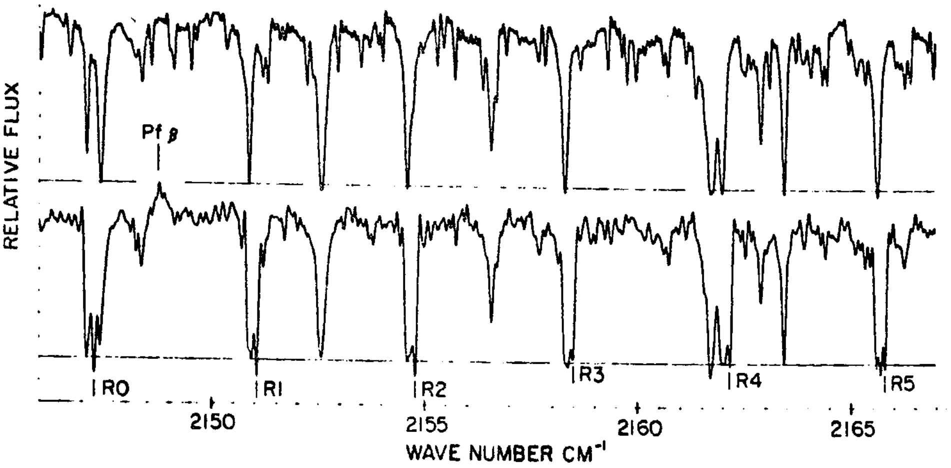

Fig. 3.4 CO absorption bands in 4.6 µm in the spectrum of the Becklin-Neugebauer source. The one at the top is a spectrum of the Sun showing the telluric absorption lines. The one at the bottom shows, in addition to the telluric lines, the blue shifted absorption lines of the BN source. This figure clearly indicates the enormous advantage of observing CO bands from outside the atmosphere. The same holds for lines of OH and $H_2O$.

(From Hall, Kleinmann, Ridgway and Gillett, Astrophys. J. (Letters) 223, L 47, 1978)

Using the Michelson interferometer at moderate resolution ($R \sim 10^2$) solid state bands in dust particles can be observed in emission and in absorption. Some of these bands have been provisionally identified as due to amorphous $H_2O$ ice, amorphous silicate and silicon carbide but the origin of several others is still unknown. Observations of the spectrum of interstellar dust in many more sources are urgently required for a better understanding of the composition and the origin of interstellar dust. In particular we may expect spectral variations as a function of dust temperature and amount of UV processing.

## H II Regions

Most H II regions are intimately linked with molecular clouds, because they form as a result of ionisation of the gas around recently born O and B stars. The Orion nebula for example, although known and studied for many years at visible wavelengths, has turned out to be the ionised front edge of a massive molecular cloud, only recently discovered. Infrared radiation is observed from dust grains, in and around H II regions, which are heated by both stellar and nebular photons. Many H II regions, embedded in molecular clouds are completely obscured in the visible by local dust. They are usually discovered by radio techniques but they can best be studied in the infrared where they emit most of their energy.

Recombination lines of Hydrogen and Helium and forbidden lines of many ions in H II regions are powerful probes of the density and temperature, and of the chemical abundances of ionised gas. For many objects obscuration by dust precludes the use of optical lines whilst certain ions do not have optical forbidden lines at all. Therefore observations of the forbidden fine-structure lines in the infrared are often the only way to study the physical conditions and in particular the chemical abundances in H II regions. Because of its high sensitivity and high spectral resolution ISO will significantly increase the number of H II regions that can be studied. This allows the possibility to determine chemical abundance gradients in our galaxy and perhaps in other nearby galaxies.

## Star Formation in Nearby Galaxies

The nearest members of the Local Group of Galaxies are the Magellanic clouds - about a factor 10 further away from the sun than the galactic centre. The clouds do not have spiral arms like the galaxy, nor do they seem to contain as much dust. However, vigorous star formation occurs at various places and there are several bright H II regions. A study of the Magellanic clouds with ISO could elucidate the similarities and the differences in the star formation processes compared with our own galaxy, in particular the role played by density waves. From a comparison of our own galaxy and the Magellanic clouds one might also hope to learn something about the relation between the chemical abundances in the gas and the amount of dust.

Similar studies to map the large scale distribution of star formation in the nearest spiral galaxies, M 31 and M 33, can also be carried out with ISO. Because these galaxies are nearby, about 50 times further away from the sun than the galactic centre, such studies combined with the known distribution of the gas and other available information could significantly increase our knowledge of how and where stars are born in galaxies.

### 3.3 Late Stages of Stellar Evolution

Probably all stars eject matter during a large fraction of their lifetime, but most prominently when they evolve away from the main sequence on to the giant branch. The mass loss is gentle (flow velocities of 10 to 20 km $s^{-1}$) so that a dense circumstellar shell is formed. As the gas cools while it flows outward, dust particles condense producing large continuum opacities at optical and near-infrared wavelengths. The lighter stars ($M \lesssim 4\ M_{\odot}$) continue to lose mass until a hot central core forms that ionises the circumstellar gas to produce a planetary nebula. More massive stars behave differently because their cores become unstable before they have shed most of their mass, resulting in a supernova. Stars in close-binary systems have a more complicated evolution because matter is being exchanged between the two stars. Novae are probably produced in this way.

By far the largest fraction of the infrared sources to be detected by ISO are giant stars of late spectral type. This is because a substantial fraction of the total luminosity of these stars ($\sim 10^4\ L_{\odot}$) is usually converted into infrared continuum radiation by dust particles in the circumstellar shell. Strong molecular absorption lines are also expected. Study of these lines with the ISO Michelson interferometer could provide insight into the kinematics of the expanding shell and into the chemical processes, in particular the formation of dust particles, in the shell. A better understanding of mass loss from late-type (super-) giant stars is of paramount importance because it recycles stellar material and thus is a significant factor in the evolution of our galaxy as well as other galaxies.

A special group of evolved objects are the Planetary Nebulae. The physical conditions in their ionised gas are similar to those in H II regions. Their continuum infrared spectra, however, peak at shorter wavelengths because there is no or little circumnebular material and they are intrinsically about two orders of magnitude less luminous. ISO can contribute here by the study of more Planetary Nebulae than is otherwise possible. Particularly fruitful will be the study of Planetary Nebulae in the inner parts of the galaxy, because they can be used as test particles to probe the gravitational potential in the galactic centre. Like H II regions Planetary Nebulae can also be used to study the galactic gradients of chemical abundances.

The oldest objects in the galaxy are the Globular Clusters whose infrared emission is dominated by late-type giants. The study of these objects with ISO to determine their sizes, their infrared light distributions and their dwarf-to-giant ratios (from the CO band), particularly in the galactic centre, will give information on the dynamical processes that ultimately destroy them.

# 4. THE TELESCOPE AND EXPERIMENT SYSTEM DESIGN

## 4.1 Introduction

Requirements for the ISO instruments are derived from the scientific objectives outlined in section 3. A model instrument payload was sketched out in the ISO assessment study (SCI(79)6). This model payload provided general inputs to studies of the cryogenics. The instruments were then studied further, particularly to define their thermal requirements in more detail and to identify the critical problem areas for development. A design study for a telescope, which is compatible with the cryostat and instruments has also been undertaken. This completes the first round in studying the whole system.

## 4.2 General Considerations

Many astrophysical studies will benefit from the highest spatial resolution possible, which is dictated by the size of the primary mirror. For the purpose of this study, it is taken at 60 cm. Reducing the diameter below 60 cm would severely compromise more detailed investigation of IRAS sources. A larger telescope is desirable, however, and considerable freedom in selecting the mirror size has been achieved by the present cryostat design.

The operating temperatures of the mirror and the other optical components are critical, and these must be consistent with the limits set by high performance detectors and the zodiacal background emission. With a detector NEP of $10^{-17}$ watts/ $\sqrt{Hz}$, at wavelengths less than 100 microns, a mirror temperature of roughly 20 K is necessary.

Silicon and germanium photodetectors will be used to cover the wavelength range 5 microns to 120 microns. Germanium photodetectors require an operating temperature around 3.5 K, compatible with the use of liquid helium for the cryogen, whereas silicon photodetectors require a higher temperature around 8 K for optimum performance. Indium antimonide detectors for wavelengths from 1 micron to 5 microns operate best at around 50 K. Low noise preamplifiers, which need to be situated close to the photodetectors also require these higher temperatures which can be achieved by insulation and self-heating. Photodetectors and preamplifiers appropriate for ISO are available now. The technology, however, is evolving rapidly and improvements can be incorporated into ISO as appropriate. Two cryogenic designs have been assessed and the results of one of them are presented in section 5.

## 4.3 Selection of the Instruments

The scientific objectives discussed in section 3 can be grouped together according to the type of measurement required (see Table 2.1) and lead to the instrument complement shown in Table 2.2.

The InSb camera array, operating in the 1 to 5 micron region, will be used for astronomical imaging and, periodically, to calibrate the alignment of the infrared optical axis. High resolution spectroscopy in the wavelength range 2-25 microns is performed by two fast-scanning Michelson interferometers, one covering the range 2-5 microns and the other 5-25 microns. The advantage of a Michelson in this application is that over a large free spectral range it has a resolution which is variable at will up to a maximum value. The third instrument of the model payload is a photometer operating from 8 to 115 microns. This instrument is not designed for scanning large areas of the sky, but rather to observe small areas at high sensitivity and with diffraction limited resolution. A detailed comparison between the performance of ISO, the Space Telescope and ground-based telescopes shows that ISO has increasing advantage over the larger, but warm, telescopes at wavelengths longer than 3 microns, particularly at lower spectral resolution.

This model payload is able to achieve the scientific objectives within the mission constraints.

## 4.4 The Telescope Design

Figure 4.1 shows an outline design for the ISO telescope. The design places the focal plane sufficiently far behind the primary mirror that a vacuum valve can be included. In this way, only the focal plane instruments and the cryogen vessels are 'cold' before launch. This saves weight since the telescope itself does not then require a vacuum vessel. For the first few days in orbit, the telescope will be 'warm' thereby promoting very efficient outgassing. The use of a fixed secondary and a moderate 10 arc minute field of view with the Cassegrain system simplifies the mechanical, optical and thermal design of the telescope. For the design of the baffling, there is considerable freedom. In figure 4.1, AA is the outer radiatively cooled baffle which is designed to minimise the thermal loading on the inner vapour cooled baffle BB. This is optimised for the operating restriction that the telescope axis will never be less than 90 degrees from the sun and for the range of angles which it will make with the Earth. Baffle BB limits the illumination of the primary mirror by off-axis radiation. CC is the secondary mirror cooled baffle and DD is the primary mirror cooled baffle situated in the obscured area of the primary. The use of baffling between the primary mirror and the focal plane is shown by EE. The optical characteristics of the telescope are shown in Table 4.1.

The primary and secondary mirrors may be made from glass-ceramics (zerodur) which will present no major manufacturing problems and will give a good optical figure with excellent stray light specifications. Thermal control of the optics assembly is by cooling coils around the experiment chamber, the primary mirror support and the baffle/strut system. Attachment of the telescope to the support ring is by three flexing joints whose lines of action intersect at the optical axis. In addition, local support to the mirrors will use three universal joints to take up rotational motion resulting from misalignment or fabrication errors. The vapour cooled baffle, radiation shields and

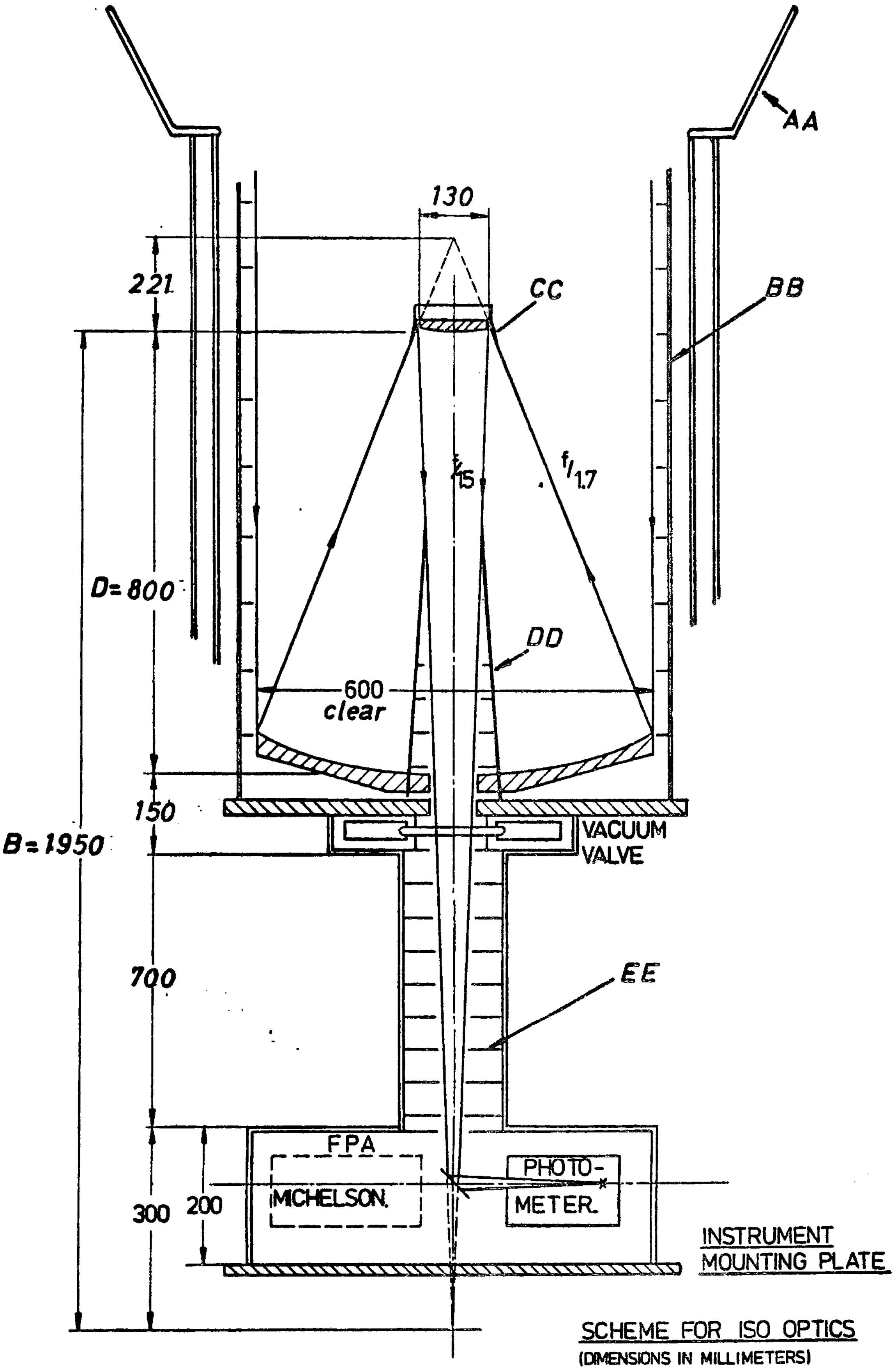

Fig. 4.1 ISO Telescope and Focal Plane Instruments Accommodation

Table 4.1 - ISO Telescope Optical Characteristics

| | |
|---|---|
| Primary mirror | 600 m Ø |
| Primary mirror focal ratio | 1.7 |
| Secondary mirror | 130 mm Ø |
| Secondary mirror focal ratio | 2.0 |
| Linear obscuration due to secondary mirror | .22 |
| Primary to secondary mirror separation | 800 mm |
| Secondary mirror to focus | 1950 mm |
| $\Delta B/\Delta D$ | 80 mm/mm |
| Plate scale | 2.6 mm/arc min |
| Saggital field curvature | -255 |
| Tangential field curvature | -200 |
| Depth of focus for 4 arc second blur angle | 5.5 |

the outer structure can be lightweight since the telescope will not be evacuated prior to launch. At that time, the cap closing the telescope aperture will only be required to maintain a dry, dust-free atmosphere within the telescope volume. Special attention will be given to the fabrication and testing of the complete optics unit independent of the rest of the cryostat and spacecraft. A fixed pyramid mirror mounted on the optical axis of the telescope distributes the beam to the four focal plane instruments. Selection of an instrument to observe a particular object is achieved by pointing the telescope so that the object comes into the appropriate area of the focal plane.

## 4.5 2-25 Micron Michelson Interferometer System

### Concept

A Michelson interferometer offers an excellent combination of performance and flexibility for fulfilling the ISO spectroscopic aims. With a relatively compact instrument, it is possible to achieve variable resolving powers (up to well over $10^4$ at the shorter wavelengths) while exploiting the multiplex, throughput and wavelength coverage advantages since the telescope and instrument are cooled. It is proposed that two rapid scanning interferometers should be used, one for the wavelength range 2 to 5 microns and the other from 5 to 25 microns. The interferometers will have different fields of view and only one unit will be in operation at any one time.

### Optical Design

The interferometers use corner cube mirrors to maximise the interferometer efficiency by enabling the two complementary output beams to be measured. There will therefore be two detectors associated with each interferometer. The sampling of the interferogram is accomplished with an auxiliary laser interferometer whose moving mirror is mounted on the moving mirror assembly of the infrared interferometer. The optical scheme is shown in Figure 4.2, where the interferometer is contained within one quadrant of the focal plane instrument volume. The input beam to the interferometer is established by the focal plane divider situated on the optical axis of the telescope. Radiation from a laser located outside the cryostat, is passed through an optical fibre and directed to both interferometers. The fringes of the auxiliary laser interferometer, measured with a photodetector, are used to trigger the sampling of the infrared interferogram. The moving mirror assembly is driven by a solenoid-type actuator to give a linear movement of 30 mm (-5 to -25) resulting in an unapodised resolution of 0.1 wavenumbers. The collimating mirror has a focal length of about 10 cm, the value being derived from the field of view, the spectral resolution (0.1 $cm^{-1}$), and the shortest wavelength in the spectral range (2 microns or 5 microns). The output condensing optics can be selected to match the optics of the detectors. The diameter of the infrared beam through the instrument will be less than 2 cm for fields of view $<$ 1 arc minute and a resolving power of about $10^4$ at 10 microns wavelength.

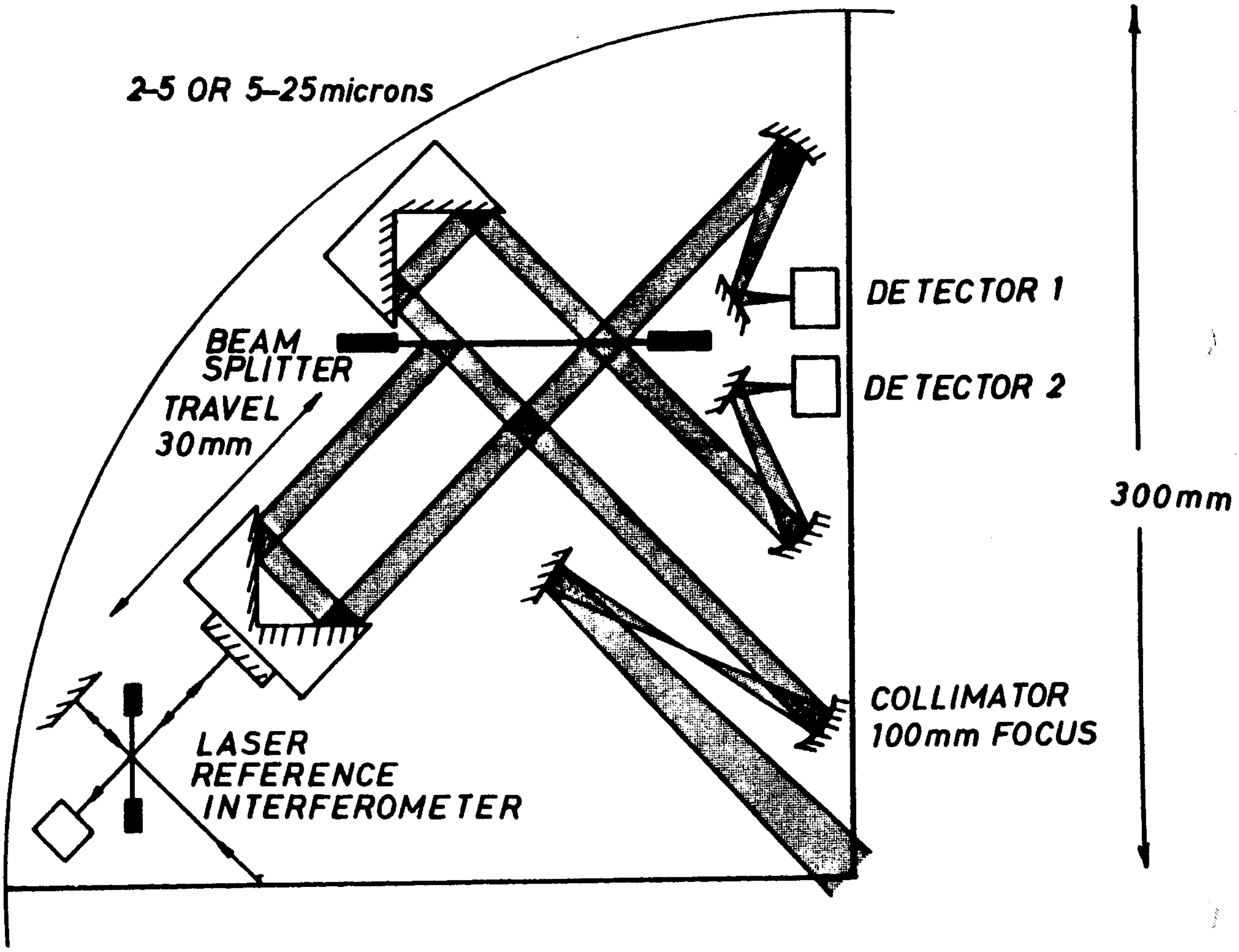

Fig. 4.2 Optical Layout for the ISO Michelson Interferometer

The observation of some bright thermal sources may produce significant extra photon noise which will limit the sensitivity to line emission superimposed on this continuum. It is unlikely, however, that this situation will warrant the complexity of providing band filters or perhaps an aperture set to observe point-like emission line sources at higher spatial resolution against the continuum background when the lines of interest are at the short wavelength end of the spectral range.

## Interferometer Drive

This is a critical element required to give a physical movement of 30 mm to one of the corner cube reflectors (for an unapodised spectral resolution of 0.1 wavenumbers). The translation speed will be in the range 0.5 to 5 mm per second set by the frequency response of the photodetectors which must match the fringe frequency of the shortest wavelength in the range of sensitivity. The development of a cooled solenoid drive, which in principle would be suitable for the interferometer, has been taken to the point of working laboratory models. The estimate for the total heat dissipation of the ISO Michelson drive of 4.3 milliwatts is based on this operational data. A system using a coil fixed to the interferometer base and with a permanent magnet (Ferroxdure 300) mounted on the moving mirror is mechanically and thermally simple and gives a good force/current ratio when cold. The speed of the movement can be controlled using the reference laser signals.

## Data and Control

Each of the detector outputs will be digitised at a rate of about 300 samples per second, with 12 bits accuracy. Allowing for the addition of up to 4 status bits per data word for both detectors gives an overall signal data rate of 10 K bits per second. Monitoring of housekeeping data including the amplifier gains and instrument setting will require less than 1 K bit per second. Circuitry will be required on-board to detect and apply some correction for spikes on the detector outputs caused by particle impact. Command words are required for selecting the short or long wavelength interferometer, the scanning length/speed, the sampling interval, amplifier gains and any filter or diaphragm positions. These can be accommodated in an 8 bit word.

## Performance and Operation

The instrument pair is designed for operation between 2 and 25 microns at any resolution up to 0.1 wavenumbers and with a field of view $< 1$ arc minute. The ability to match easily the spectral resolution with the observational requirements will aid efficient use. When operated at a temperature of less than 20 K, the telescope and instrument will contribute negligible photon noise in either wavelength band. This will allow a sensitivity of $2 \times 10^{-21}$ watts per $cm^2$ per spectral element to be obtained with a detector NEP of $10^{-17}$ watts per $\sqrt{Hz}$, assuming a 3 sigma detection level and an integration time of 30 minutes. Data from the interferometer will be telemetred to produce spectra of sufficient quality to monitor the progress of the observations. On weak sources, spectra obtained over periods up to hours may be averaged together. For telescope pointing, the Michelson interferometer establishes the most exacting requirements of the three instruments, particularly in view of the need to maintain the pointing during the measurement of a complete interferogram. For a 60 cm diameter primary mirror and the present mid-term pointing stability of about ± 4 arc seconds, measurements can only be made at the diffraction limited spatial resolution for wavelength $>$ 10 microns. In considering the possibility of a primary mirror which is larger than 60 cm, this must be taken into account.

J-fet preamplifiers will be used with the cooled detectors. These need to be situated close to the detector, but require a higher operating temperature. This can be achieved using thermal insulation and self-heating.

## Michelson Interferometer - Summary Table

**Design** Rapid scan with double output using corner cube reflectors. Separate interferometers for wavelength ranges 2 to 5 microns and 5 to 25 microns using InSb and Si : As photodetectors, respectively.

**Thermal** Interferometer operation at 8 K by attachment to the 8 K instrument mounting plate with a stability of ± 2 K. Photodetector operation at 8 K with ± 0.1 K short term stability and ± 1 K long term.

Thermal dissipation for each Michelson interferometer is budgeted as follows :

| | |
|---|---|
| moving mirror drive | 4.3 mw |
| 50 coaxial wires | 0.5 mw |
| 2 silicon detectors | $<$ 0.1 mw |
| or 2 InSb detectors | $<$ 0.1 mw |
| 4 laser photodetectors | $<$ 0.1 mw |
| 4 J-Fet preamps | 0.8 mw |

This gives a total of about 5.8 mw, the design aim being $<$ 10 mw. Conduction loss due to the wires is $<$ 0.5 mw and due to the optical fibre is $<$ 0.1 mw.

**Optical** 4 optical fibres (2 redundant) coupling 2 lasers (1 redundant) to the interferometer

Beam splitter 2-5 microns Si coated on $CaF_2$
5-25 microns Ge coated on KBr

Filters, Fabry lenses and field defining apertures to be optimised to the wavelength range. Field of view $<$ 1 arc minute. Optical stability is estimated as follows :

| | Absolute | Stability |
|---|---|---|
| Axial position of focus | ± 10 mm | ± 1 mm |
| Lateral position of focus | 0.2 mm | 0.02 mm |
| Tilt of optical components | 1 degree | 10 arc sec |

Mechanical: Each interferometer of mass 10 kg to fit into a quadrant of the cylindrical volume 600 mm diameter and 200 mm deep. Fixing to 8 K instrument mounting plate. Materials can be mostly aluminium alloy.

Electrical: Total power requirement < 20 watts, dissipated mainly in the 'warm' electronics. Each interferometer requires the following :

10 wires for the detectors
10 wires for the laser reference diodes
3 wires for limit switches
3 wires for clamp
2 wires for the coil drive

Wire material within the cryostat will be mostly stainless coax and constantin.

Data and Command: On-board deglitching. Transmit 2 x 12 bit detector output at up to 300 samples/sec giving 10 K bit/sec data rate. Housekeeping data 1 K bit/sec. All necessary commands in an 8 bit word.

## 4.6 The Photometer System

### Concept

The infrared photometer system is intended to make simultaneous observations in a selected number of wavelength bands for photometry and position measurement. Three wavelength bands within the range 8 to 115 microns have been considered for the model payload : 8-15 microns as band 1; 30-40 microns as band 2, and 80-115 microns as band 3. The instrument is not intended for surveying large areas of sky, but rather for detailed observations of sky areas which have been selected to be of potential interest, possibly from the results of an infrared survey programme such as IRAS. The 12 hour orbit of ISO will allow long integration to detect faint objects and so will be of particular application to extragalactic studies. The measurements will be made using a raster scan pointing mode or with the system operating in a step-and-integrate mode covering a matrix of observing positions and using chopping for absolute photometry. ISO will be required to determine improved positions for IRAS objects, or those from other measurements, e.g. X-ray or radio. These measurements may then be used to point the ISO telescope for spectroscopic measurements using the Michelson interferometer. The case for including polarimetry, with the consequent increase in complexity and need for fail-safe operation, is still in the balance.

## Optical Design

Figure 4.3 shows an outline of the optical design for the photometer, together with some mechanical details. Three detector modules are arranged in the photometer to observe co-centred diffraction limited fields of view, at the three wavelength bands. These are intended to measure the infrared flux emitted by point-like objects or where the highest spatial resolution is required. Three other detector modules are arranged to observe an adjacent field on the sky in the three bands, but with identical fields of view, set to be diffraction limited at the longest wavelength band. These are intended to measure the infrared flux of objects which are spatially extended on the scale of one arc minute and larger. The sensitivity of the photometer channels are consistent with the use of detectors operating with NEP's around $10^{-17}$ watts per $\sqrt{\mathrm{Hz}}$, and so approach the limit set by zodiacal emission.

A non-vignetted field of view of up to 3 arc minutes in diameter will be available to the photometer. This requires the detector modules to be arranged carefully in order not to exceed this field. The scheme shown in Figure 4.3 which uses reflection/transmission filters is good in this respect. However, the important aspect of transmission efficiency within each band must also be considered, particularly in comparison to using individual filtering for each detector, where co-centred fields of view for the three bands would not be used.

## Data and Control

The data requirements for the photometer are quite modest in comparison to the other instruments, being within 2.4 K bits per second. On-board phase sensitive detection will be required when the chopper is used, and gain switching to give wide dynamic range followed by 12 bit A/D conversion. Deglitching circuitry will also be required. Since the chopper is the only moving part in the photometer, the majority of housekeeping data will involve temperature measurements within the instrument. Commands will control the chopper operation and the external electronics for various modes of operation. A rotatable wire grid analyser may also require control.

## Operation

The photometer data will be telemetered to ground for recording and display to monitor the progress of the observation. When a raster scanning mode is employed, reconstruction and display of the telescope pointing will be required to monitor the observation. This will be essentially real-time so that it may be used to guide the telescope pointing for a spectroscopic measurement. Measurements with the 1 to 5 micron camera array are likely to be made with the photometer since together they form a photometer system spanning wavelengths from 1 to 115 microns.

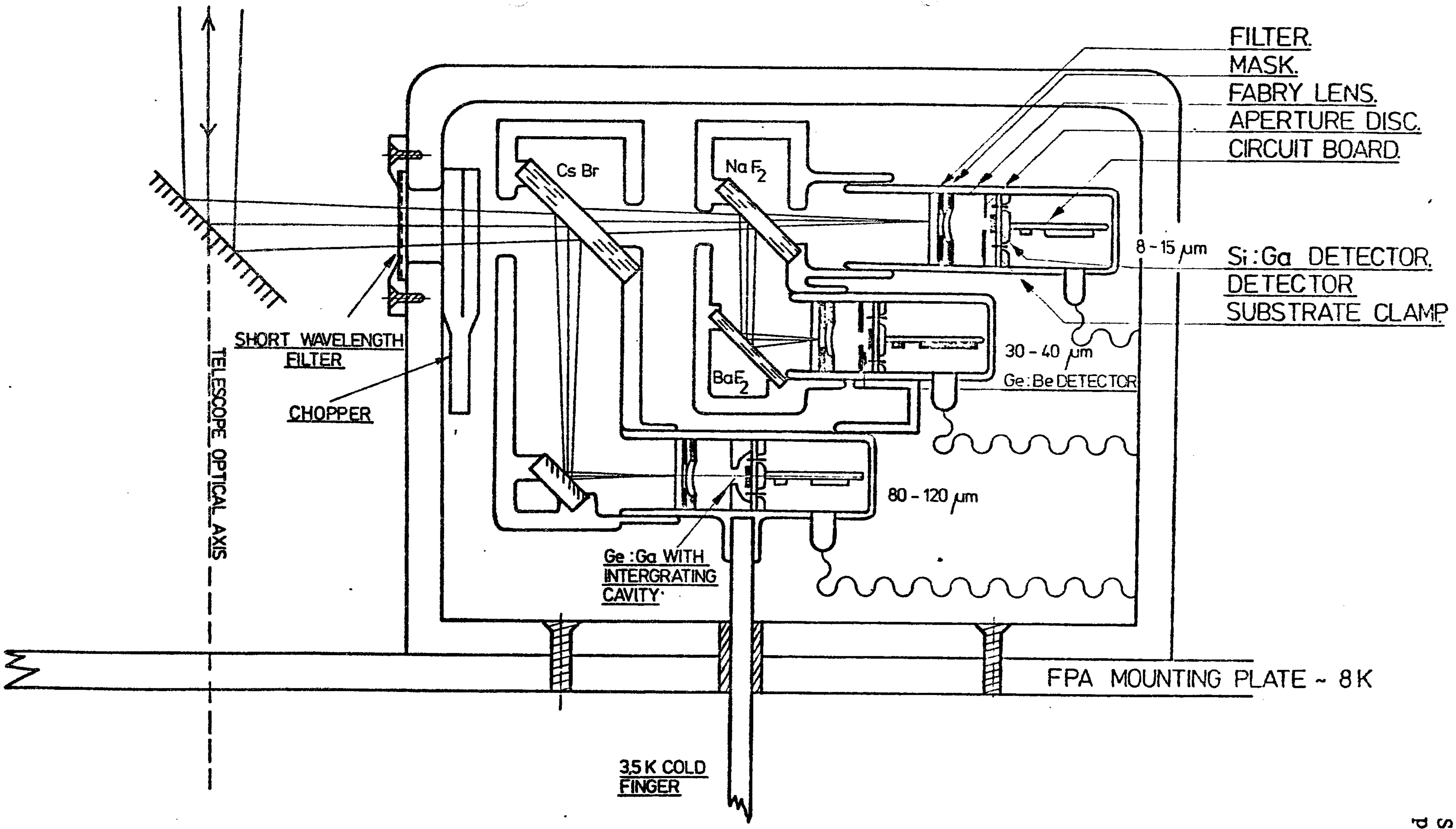

Fig. 4.3 Layout for the ISO Photometer

## Photometer - Summary Table

### Thermal

Si photodetectors (band 1) to operate at 7 K ± 2 K long term stability. Ge photodetectors (bands 2 and 3) to operate at 3.7 K + 0.5 K and -0.7 K long term stability. The short term (1 second) operating temperature stability is ± 0.01 K.

| | |
|---|---|
| Photometer body | 8 K |
| Filtering/Dichroics | 8 K |
| Chopper reference | $< 20$ K bands 1 and 2<br>$\leq$ 5 K band 3 |
| Photometer body gradients | $\pm$ 0.02 K |
| Thermal capacity | $\sim$ 4 Joules $K^{-1}$ at 8 K |

Good thermal contact is required between the photometer body and the 8 K instrument mounting plate. 3 K cold finger is required for the Ge photodetectors.

Thermal dissipation for total of 6 photodetectors together with preamps is 2.4 mw, for the chopper is $< 1$ mw and for the wires is $< 0.2$ mw.

Thermal conductance due to the 30 detector coax wires is 0.65 mw and for total of other wires is 0.1 mw.

### Optical

Lateral and axial position of focal plane, as given for the Michelson interferometer.

Filtering for the model band selection 8-15 μm, 30-40 μm and 80-120 μm obtained using CsBr, $NaF_2$ and $BaF_2$ reflection/transmission filters.

Chopper is electro-mechanically resonant type at about 20 Hz with reflecting blades. A simple calibration system will be shared with the interferometers, the main calibration being derived from observing selected stars and planets.

### Mechanical

Mass about 4 kg. Photometer to be mounted on the 8 K instrument plate with allowance for cold finger cooling for some components. Mostly aluminium alloy will be used.

### Electrical

4 wires for the chopper
30 wires for detectors
6 wires for possible preamp heating
20 wires for temperature probes
Power input to chopper $< 1$ mw with frequency $\sim$20 Hz.

### Data

Phase sensitive detection required on board. Signal channels require gain switching, logarithmic or parallel amplifiers followed by 12 bit A/D. On-board deglitching. Data rate $< 2.4$ K bits/sec, depending on operating mode.

| | |
|---|---|
| Attitude and Scanning | Offset pointing ability $5^{\circ}$ in any direction from stars down to and including 7th magnitude. Raster scan rate of 1 beam width per integration time to cover up to 10 x 10 arc minutes on the sky. |

## 4.7 1-5 Micron Camera Array

### Concept

This detector array provides the capability for two dimensional imaging and for multiband photometry in the 1 to 5 micron spectral range. It can also serve the very important purpose of determining the focal plane alignment relative to the spacecraft pointing system, for positioning the other instrument apertures. The basic design proposed is derived from a commercially available and fully developed InSb array. At the moment this would be a monolithic InSb CID array, such as the 32 x 32 GE CID with 55 x 77 micron centre pixels. Since infrared array technology is now progressing very rapidly, the actual array selected will obviously be based on the state of the art when the camera design is frozen. The array performance finally chosen will obviously be better than that described here, hence this discussion relates to a minimum performance specification.

### Optical Design

Figure 4.4 shows the scheme for the CID array mounted directly at the selected portion of the focal plane. Pupil re-imaging is not required since there is negligible background from the cooled telescope and so a very simple arrangement can be used. The cost of this simplicity is that the environment temperature for the array of 8 K is below its normal operating temperature range of 20 to 30 K. However, thermal isolation and self-heating can be used to maintain the preamplifier input transistors at a temperature higher than 20 K. A commandable heater is installed to switch the transistors on, should the array power be turned off and the transistors allowed to cool down. A filter wheel is installed in front of the array with about 16 positions. This will include filters on the standard J, H, K, L and M bands, as well as filters covering the atmospheric absorption bands which cannot be used from the ground. A moderate resolution continuously variable filter could also be included. These are all items which present no technological problems for the manufacture.

### Data and Control

Using the 12 bit A/D converter, a data transmission rate of 10 K bits per second implies the entire array can be scanned every 1.24 seconds. One 4-bit word is required to command the position of the filter wheel, and preamplifier gain control is required to match the array output to the A/D converter. The heater for the cooled array preamplifiers also needs to be commanded. Housekeeping data will include measurement of temperatures within the array enclosure and the position of the filter wheel.

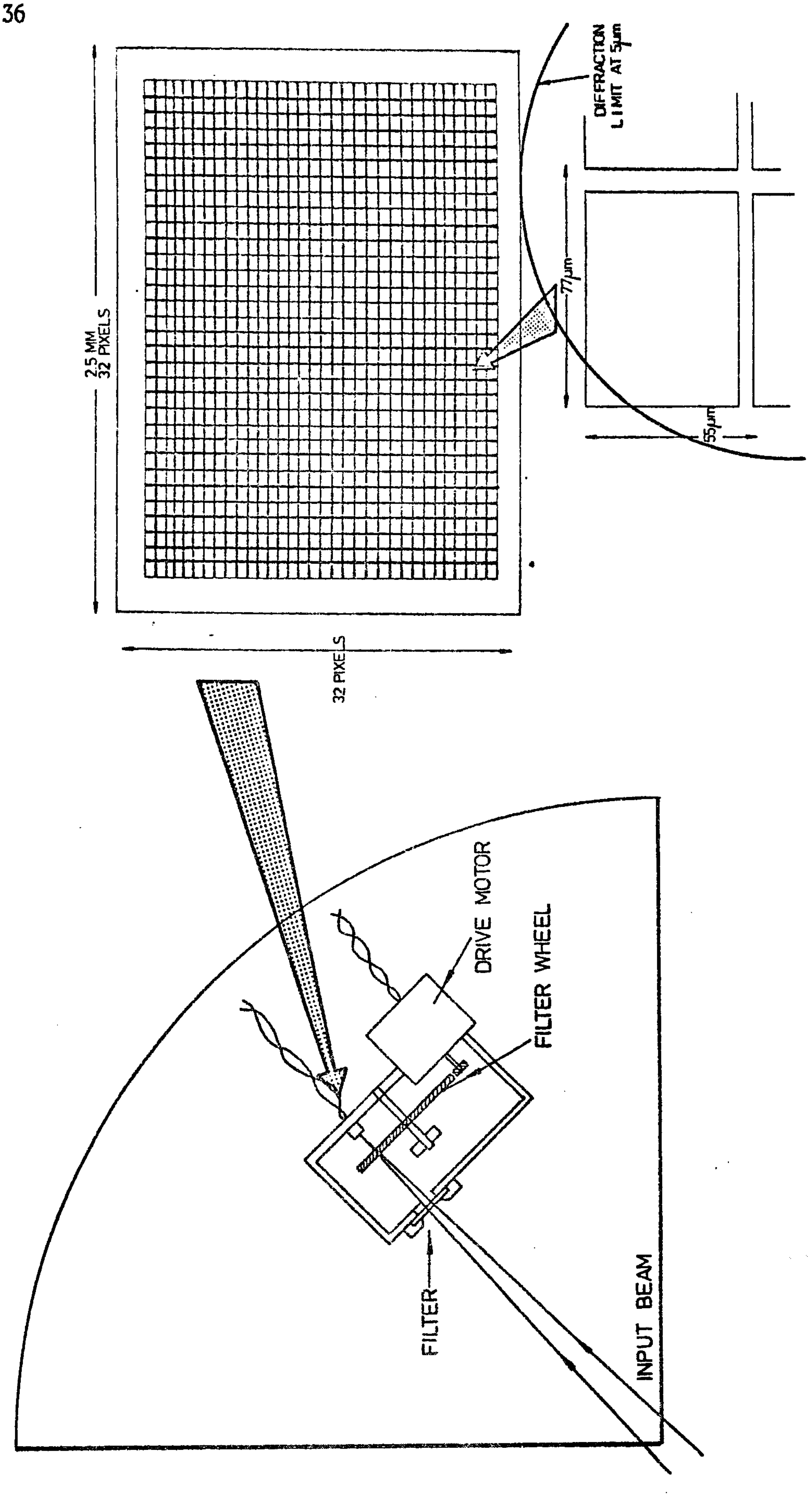

Fig. 4.4 Arrangement for the CID Camera Array

## Operation and Performance

The field of view for the whole array will be approximately 1 arc minute, but the spatial resolution obtained will depend on the read-out speed of the array and the detailed behaviour of the telescope pointing during that time. It will not be limited by the telescope optics. Image processing techniques could be used to achieve a diffraction limited resolution, which at 5 microns wavelength is about 4 pixels and at 1 micron is about 1 pixel. This iscompatible with the attitude reconstruction requirement. An NEP of $3 \times 10^{-17}$ watts per $\sqrt{\text{Hz}}$ can be expected for each element within the array. This will allow a star of magnitude 14 at 3.5 microns wavelength to be detected with a signal/noise ratio of 3 in one second.

## Camera Array - Summary Table

| | |
|---|---|
| Design | InSb camera with 32 x 32 pixels for observations from 1 to 5 microns wavelength. Could be GE CID with 55 x 77 micron centre pixels. |
| Thermal | Instrument will be mounted on 8 K plate and requires thermalisolation with self-heating to maintain the pre-amplifier transistors within the operating range of 20 to 30 K. Thermal radiation will be no problem with an environment temperature $< 40$ K. Thermal dissipation 2 mw arising mainly from the cooled preamplifiers and from the drive for the filter wheel. Conductance due to wires is $< 0.5$ mw. |
| Optical | Mounted directly at selected portion of the focal plane. 16 position filter wheel with band filters in the wavelength range 1 to 5 microns and including J, H, K, L, M, together with those covering atmospheric absorption bands. Primary calibration will be using selected stars and planets. It is essential to block UV. With f/15 beam one pixel is 1.5 arc seconds, therefore 0.4 of diffraction limit at 5 microns wavelength. |
| Electrical | 8 wires for 4 temperature sensors<br>10 wires for CID electronics (at least 2 shielded)<br>2 wires for heater<br>4 wires for filter wheel position indication<br>2 wires for filter wheel drive<br>Power input $< 20$ watts for warm electronics and $< 2$ mw for cold electronics |
| Data | With 12 bit A/D conversion, the 1024 pixels in the array can be scanned every 1.24 seconds to match a data rate of 10 K bits per second. Adjustable preamplifier gain is required. Housekeeping data for temperatures and the position of the filter wheel. |

## 4.8 Focal Plane Integration

Figure 4.5 shows the arrangement of the instruments, based on using a pyramid mirror on the axis of the telescope to reflect four positions of the focal plane radially into the focal plane volume. The Michelson interferometers are positioned so that one laser output can be used for both of the ancillary laser interferometers. This area will require careful screening so that the laser radiation does not scatter into the rest of the instrument volume. For simplicity, the instruments are shown accommodated in quadrants, but in fact this can be changed to allow for the different instrument requirements.

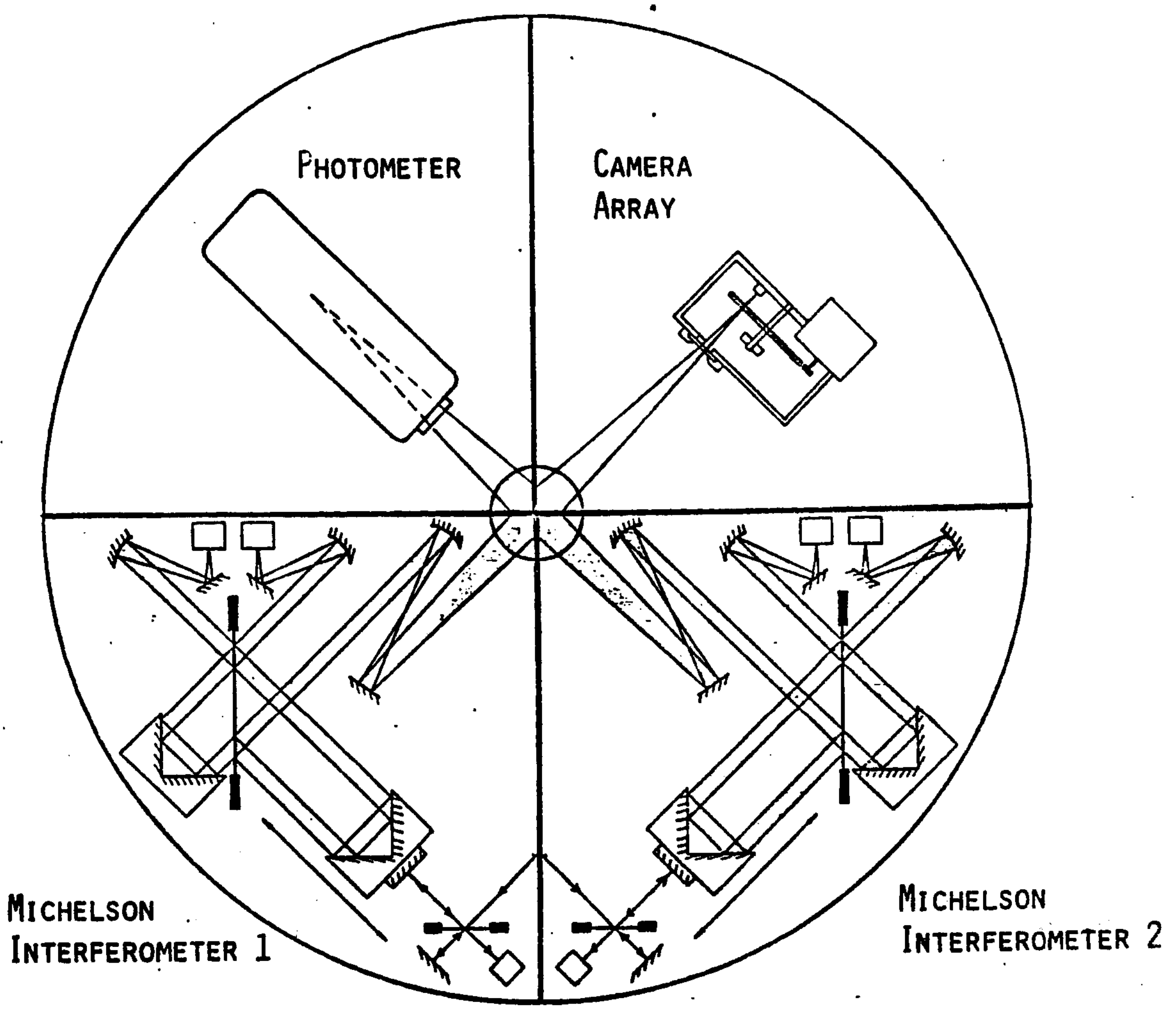

Fig. 4.5 Arrangement for Instruments in Focal Plane

# 5. THE CRYOGENIC SYSTEM

## 5.1 Introduction

Two technical assessment studies have been carried out by European industry on the cryostat. The study activity was concentrated on potential technology options followed by an initial design and problem area identification. The two concepts analysed were:

- a liquid helium cryostat,
- a hybrid liquid helium/liquid hydrogen cryostat.

The results of the studies have shown that both concepts can support the payload requirements with a minimum lifetime of 1.5 years. It later became evident, however, that only the second concept offered acceptable margins within the mass constraints imposed.by the launcher.

Two basic considerations governed the selection of this concept:

i) In addition to the superfluid helium, which is used to cool the optical instruments, a second cooling medium is used to reduce the heat load on the helium and thereby reduce the total amount of coolant for a 1.5 year mission.

ii) The design suggestion chosen allows the optical system to be kept warm during the launching phase and then to be cooled down during the first 30 days in orbit.

After an analysis of the boundary requirements which had to be met, several cooling media - including He II, supercritical He, liquid and solid H2 and Ne - were discussed. A comparison of 3 alternative cooling systems led to a selection of one system which is presented in more detail.

## 5.2 Main Characteristics of ISO

The ISO system may be divided into several major parts:

1) The optical system, consisting of primary and secondary mirror, stray light baffles and instruments. The focal plane instruments, which include Ge-detectors, Si-detectors, Michelson interferometer, photometer system, camera array and signal processing electronics, are mounted in a focal plane assembly (FPA).

2) The cryogenic system, comprising tanks, vent gas-cooled radiation shields, multi-layer insulation and operating equipment, such as temperature and pressure sensors, level indicators and valves.

3) The support system, consisting of an outer shell and support struts ensuring a sufficiently tight connection between the various parts of the total system.

4) Other spacecraft subsystems, such as a payload attachment assembly and electrical housekeeping system, are mounted in a service compartment (see Chapter 6).

The size of the optical system is mainly determined by the diameter of the primary mirror which is given as 60 cm.

Assuming a baffle inner diameter of 70 cm, a minimum baffle length of about 140 cm has to be established to reject any primary illumination of angles of incidence larger than $28^o$ off-axis. In order to allow some margin, a baffle length of 200 cm has been considered in this study.

The size of the focal plane assembly is given as a cylindrical box of 30 cm height and 60 cm diameter.

## Mission lifetime

A minimum mission lifetime of 1.5 years has been taken as a baseline. This lifetime starts from the last filling of the tanks on the ground.

## Temperatures and heat loads

Temperatures to be kept by the cryogenic system at the various points of the telescope, as well as the temperature deviations allowed, are listed in Table 5.1. Heat dissipated during operation of the Ge- and Si-detectors, as well as the experimental heat loads in the FPA, have been included in this table.

## Cooling by two cryogens

In contrast to IRAS and GIRL, where superfluid He serves as the only coolant, refrigeration of the telescope by two cryogenic fluids has been considered for ISO. The advantage of such a two-coolant system lies in the fact that, according to Table 5.1, only 55 mW cooling power are necessary at the lowest temperature levels. On the other hand, the resulting evaporation rate due to this low heat input is not enough to cover the insulation losses of the whole system. Therefore, in order to keep the He supply at a minimum, a second refrigerant will be used to deliver the necessary cooling of the shields.

Table 5.1

Temperatures and Heat Load

| | T (K) | ΔT (K) | Q (mW) |
|---|---|---|---|
| Ge-detector | < 3 | ± 0.1 | 5 |
| Si-detector | 6-8 | ± 0.2 | 10 |
| FPA | 8-15 | ± 2 | 10-40 |
| Mirror | < 20 | 2 | |
| Outer baffle | < 20 | | |

### Cool down of the mirror system

Cool down of the mirrors and the baffle system from 300 K to operating temperature will be performed only in orbit within a time interval of 30 days. By this procedure, a troublesome contamination of the otherwise cold mirrors at launch site can be prevented.

## 5.3 Discussion of Alternative Cooling Media

A temperature of $T < 3$ K is required for the Ge-detector. Therefore, only liquid He can serve as an appropriate coolant. To obtain a minimum mass flow, an operating temperature where the heat of vaporisation shows a maximum has to be selected leading to $T = 1.9$ K (He II) and $T = 3$ K (He I). Because of its excellent cooling properties (high thermal conductivity and superfluid film flow), He II is to be preferred.

To achieve some margin in the liquid enthalpy between the operating temperature and the $\lambda$-Point at $T = 2.17$ K, the temperature of the He II tank is set to $T = 1.8$ K.

The mass flow of evaporating He is determined both by the dissipating heat from the Ge-detector and the heat input to the He tank through insulation losses, supports, etc. The enthalpy of the vented gas is used to cool the Si-detector and FPA at a temperature of $\approx 6$ K and $< 15$ K, respectively.

After leaving the FPA heat exchanger, the cold He gas will be directed to the vent gas circuit which absorbs part of the insulation losses of the total system. To compensate for the remainder of the insulation losses, a second cooling circuit is necessary.

Among the various refrigerants, supercritical He (sc He), liquid and solid hydrogen (LH2, s-H2) as well as liquid and solid neon (LNe, s-Ne) are potential candidates.

Table 5.2 compares the cooling capacity (gas enthalpy plus heat of vaporisation of sublimation) stored in different cooling media between their boiling (or solidification) temperature $T_0$ and a final temperature of 200 K, which corresponds to the skin temperature of the system in orbit.

Since the mass as well as the volume serve as criteria for the layout of the cooling system, Table 5.2 shows both the cooling capacity per gram (J/g) and the cooling capacity per litre (kJ/l) of the stored cryogen.

Comparing H2 with Ne, the 55% larger cooling capacity per volume of Ne is striking. However, this advantage is counterbalanced by the large density of neon. For instance: a cooling power of 4 W over a period of 1.5 years requires 64 kg LH2 but 710 kg LNe. The use of neon would imply a massive support structure of the tank, giving rise to increased heat input to the liquid.

Considering the triple points of H2 (T = 13.8 K, p = 0.07 bar) and Ne (T = 24.6 K, p = 0.43 bar), it can also be seen that H2 offers more flexibility regarding the operation temperature and pressure than neon.

Furthermore, since the heat input to the He II tank through supports and radiation is determined by the temperature of its surroundings, a low boiling point of the second cooling medium is more favourable.

Table 5.2

Comparison of Different Cryogens

| | Temperature $T_0$ (K) | $\Delta h = h$ (200 K) $- h$ ($T_0$) | |
|---|---|---|---|
| | | $\Delta h$ (J/g) | $\rho \times \Delta h$ (KJ/1) |
| He II | 1.8 | 1052 | 156 |
| sc. He (15 bar) | 5.5 | 1032 | 153 |
| LH2 | 20 | 2921 | 207 |
| LNe | 27 | 266 | 320 |
| solid H2 | 13 | 2971 | 259 |
| solid Ne | 24 | 287 | 413 |

$\Delta h$ (J/g) indicates cooling capacity per gram; $\rho \times \Delta h$ (kJ/1) per litre stored cryogen.

Compared to LH2, solid H2 offers an even greater cooling capacity. The main reason for this is the additional heat of melting. In fact, solid hydrogen has already been used in space technology (e.g., NIMBUS).

The use of solid hydrogen, however, brings a number of technical problems:

- heat transfer between the tank walls through subliming H2 gas to arbitrarily scattered solid blocks of H2 (heat transfer may be improved by internal tank structure);
- due to the low thermal conductivity of solid H2, there is a risk of locally melting hydrogen during short periods of increased heat input (hot spots);
- the complete filling of the tank with solid H2 presents a special problem. Experience with solid ammonia and methane shows that cavities develop during the freezing process and that these cavities cannot subsequently be filled again with either liquid or solid hydrogen. This reduction in the apparent density of the solid hydrogen requires a larger tank than expected.

- due to the low storage pressure of solid hydrogen, the tank has to be closed during the pre-launch operations. During this time, the vent gas cooling of the radiation shields is interrupted and thus heat input to the tank is increased drastically.

On the other hand, there is a theoretical gain of 8% in mass and 25% volume for the coolant. This has to be weighed against the above-mentioned difficulties. A more detailed study of the solid H2 solution is under way at ESTEC.

As experience to date is limited to small-scale applications of solid H2, an LH2 system is, therefore, preferred to a system with solid H2. If, after further research, the use of solid H2 should be selected, then hydrogen could be solidified in a suitable cooling circuit which has to be enclosed in the H2 tank without changing too drastically the proposed concept.

Supercritical He has also been considered. As is evident from Table 5.2, the cooling capacity per gram of supercritical He is about a factor 3 less than of liquid hydrogen. The use of this cryogen has been rejected because of the total mass and volume constraints.

These considerations led to the selection of LH2 as the preferred secondary coolant.

### 5.4 The He II/LH2 System

This system, using He II and LH2, is characterised by two independent cooling cycles (Fig. 5.1).

Evaporation of He II (at a temperature of 1.8 K) will be provided both by heat input from the surroundings and the thermal coupling of the Ge-detector to the He II tank. A resulting He mass flow of 1.18 mg/sec at a pressure of 17 mbar passing the He II phase separator is enough to keep Si-detector and FPA at their operation temperatures.

LH2 enclosed in the LH2 tank at a temperature of 20 K and a pressure of 1 bar is evaporating via a special H2 liquid gas phase separator and directed to the vent gas system.

When referring to LH2, it is understood that only para-H2 can be used for application in ISO, in order to avoid unwanted evaporisation of H2 by conversion of normal H2 into the stable low temperature para-modification.

By producing a slight overpressure in the LH2 bath during pre-launch operation, a pressure difference in the vent gas system is obtained. This ensures an active cooling of the radiation shields during the launching phase.

At first sight, it seems favourable to combine He and H2 vent gas to save one vent gas system. On the other hand, this imposes several problems, e.g., the risk of freeze-out of H2 gas at the cold He vent tube and the difficulty of an independent regulation of the He and H2 mass flow, respectively. In view of these complications, separate vent lines for H2 and He will be used.

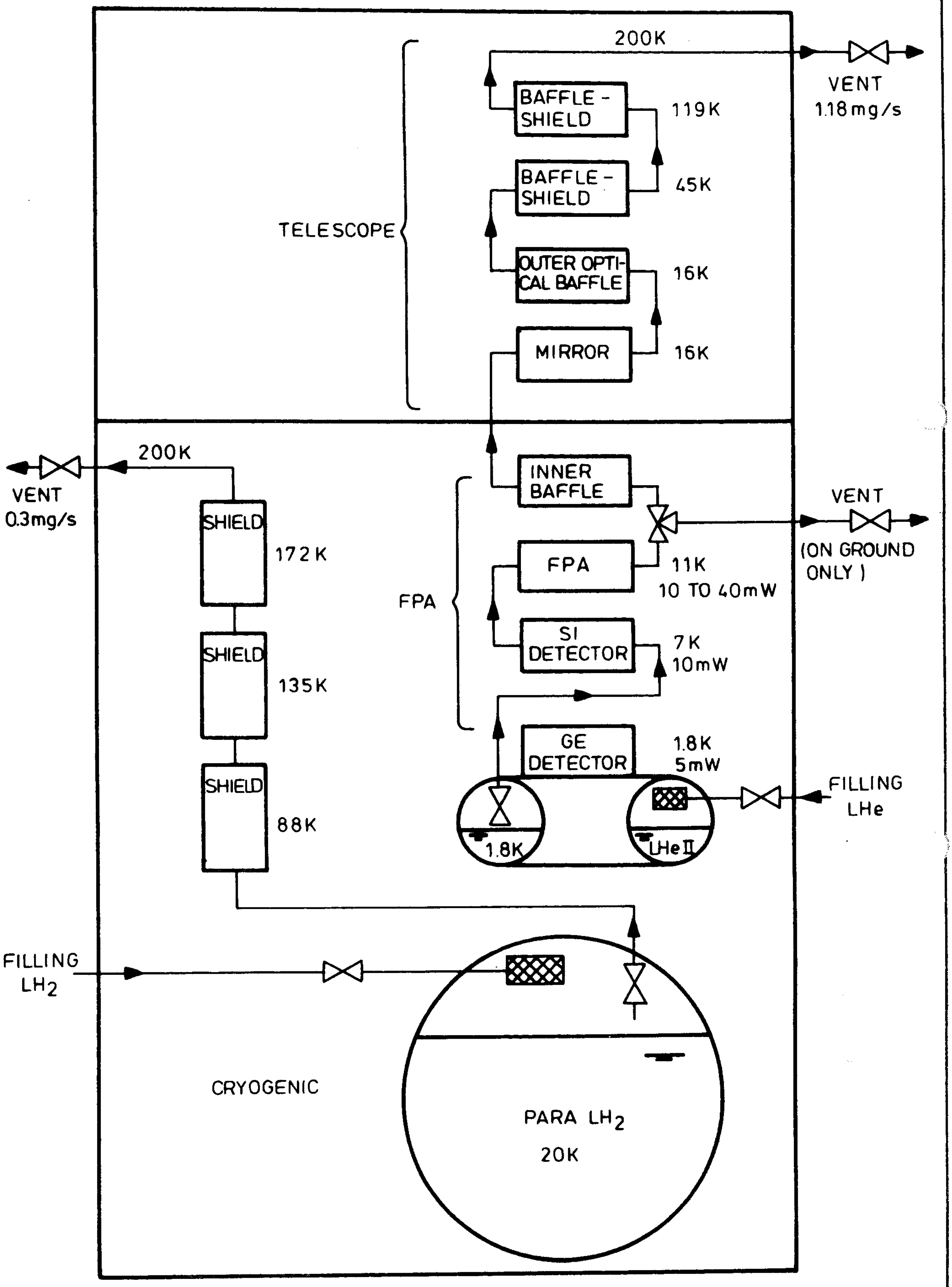

Fig. 5.1 The He II/LH2 System

### The gas flow logic

By thermal coupling of the Ge-detector to the LHe II tank (temperature 1.8 K) and by heat input from the surroundings, a small amount of He gas vaporises. This cold He gas is now used to cool the Si-detector and optical experiments, which are surrounded by the FPA, to operating temperature. During pre-launch operations, when the mirror has to be kept warm, the He gas subsequently leaves the ISO cryostat and is channelled into a He vacuum pump. For cooling down of the mirror in orbit, the He gas is channelled to the mirror heat exchanger via the vent gas system coupled to an inner baffle. After having passed the outer baffle, the He flow cools the two radiation shields, thereby absorbing the heat input from the surroundings of the outer optical system.

The H2 gas which leaves the LH2 tank (temperature 20 K) through a special liquid vapour phase separator, serves as a coolant for the cryostat shields. Three H2 gas-cooled radiation shields act as thermal insulation for the LH2 and the LHe II tank.

The selection of two radiation shields around the outer optical system as well as three radiation shields around the H2/He tanks is based on a first thermal analysis.

Temperature control is performed as follows:

The Ge-detector is thermally directly connected to the He tank, and cooling of the Si-detector and of the FPA instruments is effected through heat exchangers. They are designed for the maximum heat input of each component. Electrical heaters ensure a constant temperature at the instruments should a reduction of heat dissipation occur. This provides a simple and reliable temperature control for the various experiments. If a fixed temperature on the mirror and FPA is not required, the above-mentioned heater could be dispensed with, allowing the FPA and mirror temperature to float down whenever the heat dissipated by the Si-detector and FPA is reduced.

The temperature achieved at each level is also shown in Figure 5.1 and is fully compliant with the requirements of the experiment.

The tanks required are 400 l for H2 and 500 l for the He II. This includes 20% cryogen reserve in addition to what is required for the 1.5 year lifetime.

## 5.5 Detailed Design Description

The ISO design, as shown in Figure 5.2, is basically divided into two main parts: the cryostat system and the telescope system. The cryostat incorporates the two cryogenic tanks, the insulation system and the FPA (9) with its instruments. The telescope incorporates the primary (13) and secondary mirror and the outer baffle (21). One of the main criteria in the design of ISO is that the outer optical system is thermally separated from the cryostat cooling system. Thus, ambient temperature is

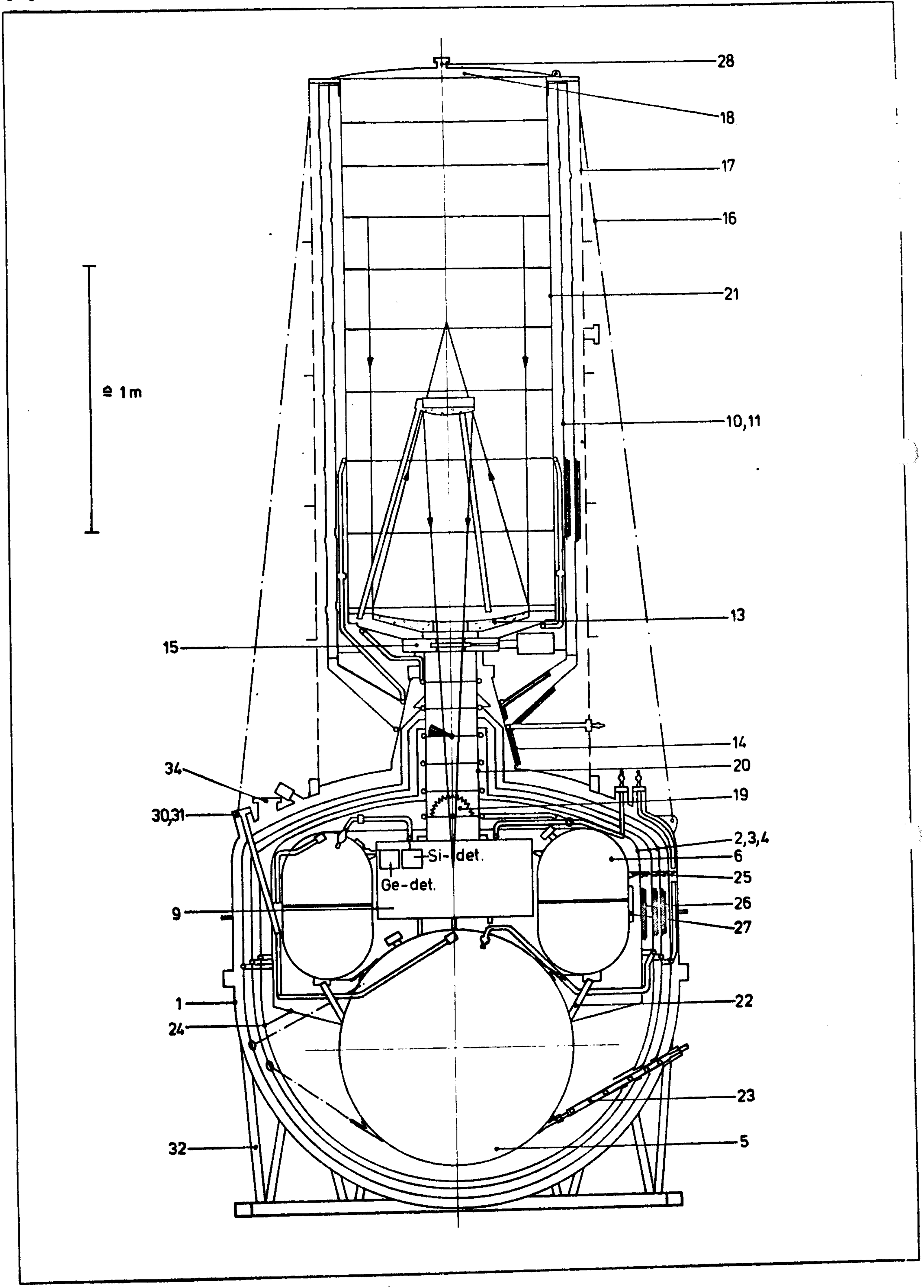

Fig. 5.2 ISO Cryostat Design

maintained during launch and flight. The advantage of this principle exists in the fact that the outer optical system does not need to be included in the vacuum vessel of the cooling system. And this, again, results in considerable savings in weight. At the same time, the contamination risk for the optical parts is decreased, since cooling down is not effected until optimum vacuum conditions in space have been reached.

### Cryostat system

The arrangement of LH2 tank (5), LHe tank (6) and FPA (9) was chosen so that the evolving shell comes close to spherical geometry. This design results in minimum volume, surfaces and weight for the cryogenic system.

### LH2 tank (5)

Volume : 400 1

Weight : 50 kg

Material: CrNi steel

The spherical tank represents the ideal tank geometry. The ratio of surface to volume has its minimum. Compared to other tank geometries, it achieves the highest stability.

The material has to fulfil the following requirements:

- good mechanical properties against cracking (breaking) at low temperatures
- high yield point (elastic limit)
- high modulus of elasticity
- good weldability and tightness of welding seams
- low density.

Due to reliable manufacturing, high operating reliability, low costs and trouble-free connection possibilities of the pipe system, CrNi steel was chosen as tank material.

Fixing of the tank suspension is accomplished by two load carrying rings, equalising the load distribution.

The outer surface has to be well finished, to obtain optimised radiating conditions.

### LHe tank (6)

Volume : 490 1

Weight : 90 kg

Material: CrNi steel

The toroidal tank has a disadvantageous ratio of surface to volume. This tank configuration was kept to preserve an optimum ratio of surface to volume for the whole cryogenic system.

The material selection is equivalent to that for the LH2 tank.

Support results from an array of glass fibre reinforced plastic (GFRP) rods to the LH2 tank.

The outer surface has to be well finished to obtain optimised radiating conditions.

Shields (2, 3, 4, 24)

The shield (24) is directly fixed to the H2 tank. It surrounds the LHe tank (6) and the FPA (9).

The shields (2, 3, 4), which are thermally connected to the exhaust pipe system, are cooled by the H2 vent gas.

As material, aluminium alloy (3.3214).has been selected because of its good heat conductivity, low density and strength. To preserve sufficient form stability, the shields have reinforced seams in their cylindrical section of the flange connection with the outer shell.

This construction allows assembly activities at the LHe tank (6) and pipe system without dismounting of the LH2 tank (5) and its shields.

The extension of the shields around the inner baffle (20) are also detachable to simplify assembly activities at the FPA (9) and the pipe system without dismounting of the tanks (5, 6) and their shields.

The shields (2, 3, 4) are fixed to the LH2 tank suspension (23).

During ground and flight phases, further support is given by the buffers (25).

These buffers have contact only when high acceleration forces are incurred (e.g., during the start). Under zero g conditions, they do not represent any heat bridges to the tank.

The shield surfaces are polished or coated to achieve low emissivity.

Outer shell (1)

Weight : 230 kg
Material : Al alloy

The outer shell is of a welded construction or, alternatively, is shaped by a milling machine out of thick-walled material.

For assembly reasons, the outer shell is divided by a flange.

The outer shell is attached to the spacecraft by a special payload attachment assembly (32). The upper part has a large cut-out stiffened by a flange. The mirror attachment system (14) and the test vessel (17) are mounted on this flange. This cut-out makes a simple disassembly of the FPA (9) possible without dismounting the tanks (5, 6), valves and pipe systems. Dismounting of the exhaust pipes to and from the FPA and to the inner baffle (20) at their flange connections cannot be avoided.

Supports (22, 23, 25)

The optimum material has a very high ratio of modulus of elasticity, E, to heat conductivity, $\lambda$. For GFRP, the ratio E:$\lambda$ is with 90 x $10^7$ NK/Wcm essentially higher compared to the other possible materials (CrNi steel: 3 x $10^7$; titan: 17 x $10^7$); thus, GFRP was chosen.

The supports have to be designed in such a way that the resonance frequency of the suspended mass does not go below 40 Hz.

It is planned to suspend the LH2 tank (5) with 8 upper and 8 lower meridian-oriented drawstrings of loops of GFRP material (23).

The LHe tank (6) is directly supported by an array of GFRP pipes (22) on the LH2 tank (5).

To protect the He tank against radial displacement caused by high acceleration during the start phase, the He tank is supported by buffers (25) against the outer shell (1) without having direct contact at rest or in orbit.

The cryostat and the outer optical system are connected by the inner baffle (20) and a conical mirror attachment neck (14). During ground operations there is a large temperature gradient along the inner baffle, while the mirror attachment neck is kept at constant ambient temperature. Once in orbit, however, the inner baffle is to be kept at a constant temperature of 16 K, whereas along the attachment neck there exists a large gradient of temperature.

These requirements are met by the proposed design which consists of:

a) Mirror system attachment neck (14)

This neck needs a high stiffness to guarantee the minimum resonance frequency of 40 Hz and must also be vacuum tight.

Because of its high stiffness to conductivity ratio, it is proposed to use GFRP.

b) Inner baffle

The FPA (9) is suspended by the inner baffle (20). The material must fulfil the same criteria as for the conical piece of the mirror attachment system; however, leak-proof properties under vacuum conditions are not required there.

During the operation tests at the ground test laboratory and during the launch operation, a good thermal insulation between the gate valve (15) and the FPA (9) is required. The optical path is closed by two inner optical shutters (19). They could consist of Al vapour coated foil folded during operation in orbit.

The He exhaust pipe integrated in the inner baffle has good heat-conducting contact with the baffle diaphragms but has minimum heat conductivity in the longitudinal direction of the inner baffle.

To insulate the inner baffle against radiation from warm parts of the mirror attachment neck, the inner baffle is surrounded by extensions of the tank radiation shields.

### Pipe system and valves

The H2 and He fill pipes are made of GFRP. All others are composed of low-conduction steel, the advantage being that steel can be welded reliably.

The valves are all ON/OFF type, such as those used on GIRL and CRHESUS cryostats. One large gate valve (15) remains closed during ground operation, in order to maintain the vacuum around the H2 and He tanks. In orbit, this gate valve must remain open to allow the infrared radiation to reach the FPA.

### Multi-layer insulation (26)

The superinsulation consists of 20 layers of aluminized and perforated foil, coating the shield surfaces. Nylon pins, fixed in the shields and connected to the next set of pins by a nylon network, hold the foil layers together.

The superinsulation must be very carefully mounted at the dividing lines of the shields, otherwise the quality of the superinsulation may be considerably diminished.

Sufficient experience in the manufacture of many cryostats and superinsulated pipes exists in Europe.

### Adsorber (27)

The LHe tank (6) is connected to an activated charcoal adsorber (27) which serves to adsorb He and H2 leak gas during ground operation tests and launch operation.

Note: In case solid hydrogen is used instead of liquid hydrogen, a heat exchanger is inserted into the tank. By cooling with liquid He, the hydrogen is frozen. In order to improve the heat transfer to the solid hydrogen, a special internal tank structure is provided (e.g., Al foam).

### Telescope system

Mirror (13)

The mirror is designed as cassegrain optics with 600 mm diameter. The mirror platform is connected to the mirror system attachment by the gate valve (15). He vent gas cools the mirror by cooling coil contacting the mirror platform.

Outer baffle (21)

Weight : 50 kg

Material: Al alloy

The outer baffle consists of a cylindrical mantle with approximately 800 mm diameter with inserted baffle rings.

Cooling of the outer baffle is performed by He vent gas streaming through a spiral cooling pipe around the baffle.

The outer baffle (21) is flanged to the mirror platform. Together with the shields, the baffle is tightened by steel cables to the outer shell (1) of the cryogenic system.

For radiation cooling purposes, the inner side of the baffle is blackened, the outside polished or coated.

Shields (10, 11)

Weight : 35 kg

Material: Al alloy

Test vessel (17)

Material: C steel

For testing the telescope on the ground, the mirror system is provided with a vacuum case (test vessel, 17).

## 5.6 Mass Budget and Dimension

A detailed mass breakdown of the cryogenic and optical system is given in Table 5.3.

The total mass estimated at this stage of 792 kg is well below the maximum allocation of 950 kg. The margin is considered sufficient to proceed to a next phase of development.

The total height of the system is 4300 mm for a maximum diameter of 1700 mm and is compatible with an Ariane launch.

## Table 5.3

## Summary of Materials, Mass Budget

| ISO Components | Part No. (cf Fig.5.2) | Material | Volume Ltr | Weight kg | Total Weight kg |
|---|---|---|---|---|---|
| Cryosystem | | | | | |
| Outer shell | 1 | Al alloy | | 230 | |
| LHe tank | 6 | CrNi steel | 490 | 90 | |
| $LH_2$ tank | 5 | CrNi steel | 400 | 50 | |
| FPA | 9 | | | 20 | |
| Shields | 2,3,4,24 | Al alloy | | 80 | |
| Insulation | 26 | (Mylar) | | 10 | |
| Inner baffle | 20 | GFRP | | 11 | |
| Gate valve | 15 | Al alloy | | 10 | |
| Supports | 22,23,25 | GFRP | | 30 | |
| Mirror system attachment neck | 14 | GFRP | | 8 | |
| Tubes + valves | | CrNi steel | | 15 | |
| Absorber | 27 | | | 2 | |
| | | | | 556 | 556 |
| LHe mass | | | 440 | 67 | |
| LH2 mass | | | 360 | 26 | |
| | | | | 93 | 93 |
| Optical System | | | | | |
| Mirror | 13 | | | 40 | |
| Outer baffle | 21 | Al alloy | | 50 | |
| Shields | 10,11 | Al alloy | | 35 | |
| Insulation | 26 | (Mylar) | | 5 | |
| Outer optical shutter | 18 | Al alloy | | 8 | |
| Tubes + valves | | CrNi steel | | 5 | |
| | | | | 143 | 143 |
| | | | | TOTAL | 792 kg |

## 5.7 Technical Problems and Critical Components

It is quite obvious that, after a first assessment study of ISO, a number of technical problems remain. There are also some components which are 'critical' in the sense that they have to be available and reliable for this project.

The technical problems are mainly associated with the size of the ISO cryostat. ISO is larger than any cryostat built up to now and will, therefore, require more effort at the detailed design stage to solve these technological problems.

The critical components which have been identified are:

He II phase separator
H2 phase separator
Mirror attachment neck
Cold valves
Cold pressure sensors.

These are critical for the performance of the system and its lifetime.

He II phase separator

Two alternatives are under development in Europe, and satisfactory results have been obtained up to now.

H2 phase separator

ESTEC is undertaking some development on this subject, and at least one possible solution has been identified.

Mirror attachment neck

This glass fibre part has to be developed. A great deal of experience exists on this material in Europe and this is not considered as being a difficult problem.

Cold valves and cold pressure sensors

These exist for ground applications, but are not commercially available for space application. A design and qualification programme will have to be undertaken. Furthermore, it is expected that the good experience with CRHESUS valves will be applicable to ISO.

# 6. THE SPACECRAFT

## 6.1 Requirements and Constraints

### 6.1.1 Orbit and launcher

A basic requirement of this mission is to maximise real time operation of the experiments. To allow continuous real time operation from one European ground station, a 24-hour geosynchronous orbit would be necessary. For this orbit the present Ariane I and expected Ariane II and Ariane III capabilities would impose unacceptably small margins to the derived spacecraft mass.

A low Earth orbit was abandoned, since this would not allow real time operations. Therefore, as a baseline for this assessment study a 12-hour elliptical (1000 km, 40 000 km) equatorial orbit has been taken. The satellite mass allowed on this orbit is 1535 kg for Ariane I and 1840 kg for Ariane II.

Analysis of the particle environment has indicated that on this orbit the high proton flux could disturb the measurements for about 1.5 hours around perigee passage.

To minimise the influence of the residual atmosphere (drag and contamination), the perigee height needs to be above 1000 km. Since this orbit cannot be reached by direct injection, an on-board propulsion system (six ION hydrazine thrusters) is required for perigee raising and synchronising with the Earth's rotation. Due to luni-solar perturbations, the perigee and apogee altitudes will vary in the course of the mission. From time to time, orbit corrections will be needed to keep the perigee height within the acceptable limits.

### 6.1.2 Ground network

To maximise real time operation, Villafranca (Spain) and Carnarvon (Australia) have been assumed as ground stations. Due to the fact that both stations are not 180° apart in longitude, a total ground coverage of 93% of the time per day is obtained. In fact, the part of the orbit where data cannot be recovered is around perigee where, due to high proton fluxes, measurements are disturbed in any case. In view of the small data loss, on-board data storage is not justified.

## 6.2 System Description

### 6.2.1 Configuration

An outline of the proposed ISO spacecraft is illustrated in Figure 6.1. Essentially, the design can be considered as consisting of 3 main elements:

- cryostat
- telescope
- sub-system compartment.

Within the assessment study preliminary support sub-system designs were explored to the appropriate depth and proposals are included in this report.

It is proposed to decouple the cryostat from the sub-system compartment such that thermal flux radiated and conducted from the sub-systems towards the cryostat is minimised. This also has the additional advantage of allowing separate design development and testing of the cryostat and of the sub-system compartment.

In order to minimise thermal coupling with the cryostat, the upper floor of the sub-system compartment would be covered with superinsulation. Equipment boxes would be installed on the side wall and lower floor. The solar array and antenna booms are folded during launch and supported by the side walls.

### 6.2.2 Satellite resource budget

Preliminary mass and power budgets have been established and these are summarised in the following table.

| | MASS (kg) | POWER (W) |
|---|---|---|
| - Telescope (incl. cryogen, experiments, interface skirt sun baffle) | 792 | 80 |
| - Subsystems | | |
| AMCS | 81 | 80 |
| Power (incl. battery charging 95 W) | 86 | 100 |
| OBDH - TM/TC | 27 | 70 |
| Thermal | 15 | 2 |
| Harness | 30 | - |
| Structure | 90 | - |
| Satellite in final orbit | 1121 | 332 |
| Orbit Control System | 171 | - |
| Satellite at launch | 1292 | 332 |

| Launch capabilities | Ariane I : | 1535 kg |
|---|---|---|
| | Ariane II : | 1840 kg |

The power budget reflects the worst case requirement from the solar array. Note that 95 W are included for battery charging to a level which can sustain operations during the maximum eclipse time of 2.4 hours.

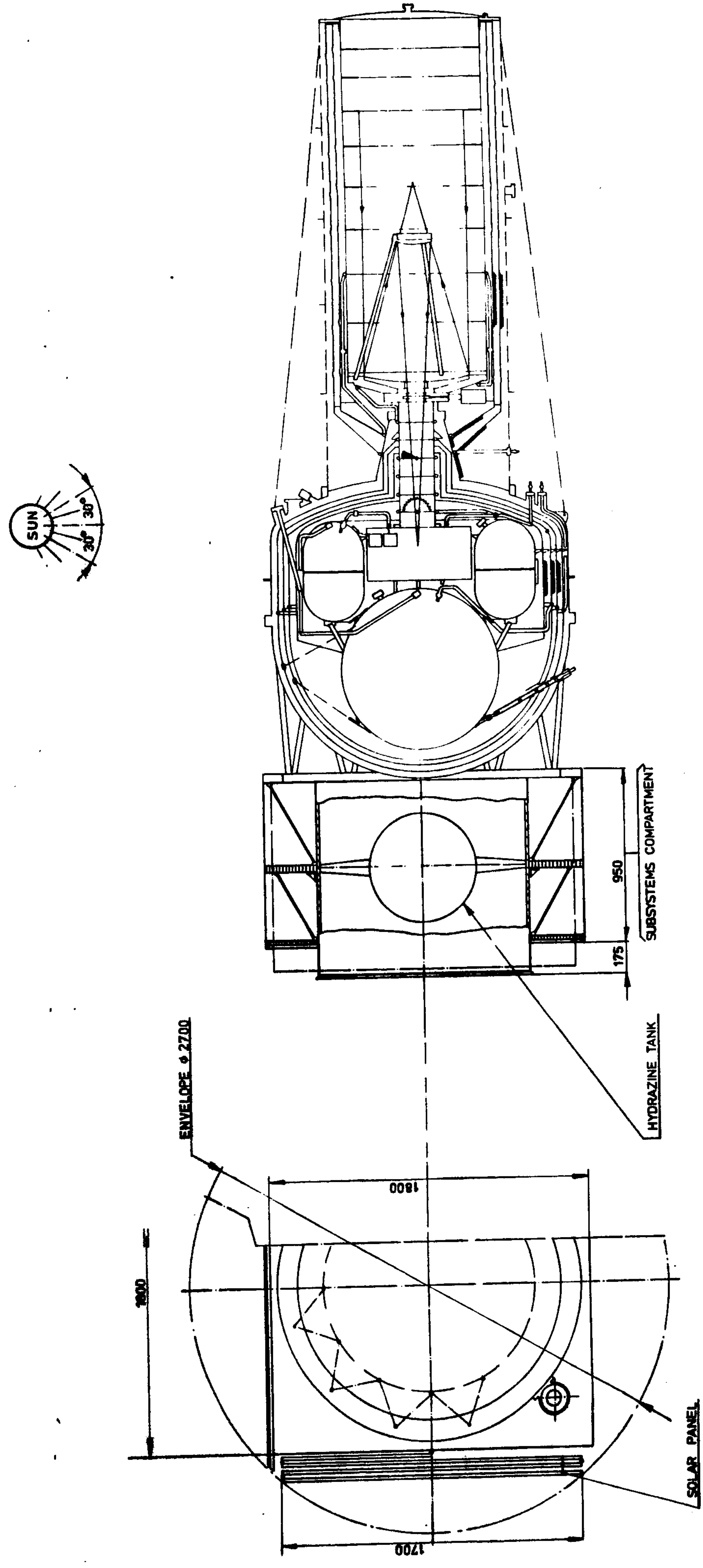

Fig. 6.1 ISO Configuration

## 6.3 Sub-system Description

### 6.3.1 Attitude measurement and control system (AMCS)

The main pointing and control requirements of the ISO mission may be summarised as follows:

- The telescope optical axis can be pointed anywhere within ± 30° from the plane perpendicular to the Earth/Sun vector except within a few degrees of the Earth. This requirement is dictated by the need to minimise the heat load on the telescope.

- Optical axis pointing on the celestial sphere is:

| | | |
|---|---|---|
| Absolute pointing accuracy | | ± 10 arc secs (r.s.s.) |
| Pointing stability: | | |
| | long-term | ± 6 arc secs (r.s.s.) for a period of 60 minutes |
| | short-term | ± 2 arc secs (r.s.s.) for a period comparable to the AMCS gas jet limit cycle |
| Attitude reconstitution (a posteriori knowledge) | | preliminary requirement ± 1 arc sec (r.s.s.), but it is being investigated whether this may be relaxed to ± 5 arc secs |
| Attitude roll error about the optical axis | | not scientifically important, an error of 0.5 degree is acceptable |

- No particular constraint on the time required to slew from one target to another, although the selected observation programme sequence would attempt to minimise large slew angles, in order that maximum observation time can be achieved.

Target attitude sensing reference will be provided by two star sensors which are boresighted with the telescope optical axis. The star sensors would be mechanically fixed to the telescope structure and pre-aligned with the optical axis prior to launch; no in-orbit alignment is foreseen. In addition to the star (boresight) sensors, sun sensors will be provided for a second reference axis; these EXOSAT-type sensors control the telescope roll around the line of sight and also provide solar array pointing reference towards the Sun. Note that gyros are also included, to provide back-up second axis inertial reference during eclipse periods and during manoeuvres; these gyros may also be similar to the EXOSAT type.

For attitude control actuation, a set of 4 reaction wheels (5 Nms) will be provided (3 orthogonal sets plus one skewed); hydrazine thrusters will provide de-saturation of the reaction wheels at the appropriate time intervals.

The proposed concept is now becoming somewhat standard for 3-axis controlled spacecraft, and it is considered that the proposed requirements could be met by such a system.

### 6.3.2 Power sub-systems

The power requirements (332 W) given in the table in Section 6.2.2 will be provided by solar arrays based upon the ECS design. Two ECS panels provide 255 W. Four ECS panels would provide 510 W at the end of life at 30° sun aspect angle.

The requirement being 332 W could, therefore, be achieved by use of 3 ECS panels: 2 active panels on one array side and one active panel plus dummy (for balance) on the other side.

For eclipse operation, two 23 Ah Ni Cd batteries are provided which are recharged from the solar array. Power distributed will be provided by a 28 V DC regulated bus.

### 6.3.3 On-board data handling sub-system (OBDH)

The data handling sub-system proposed for this mission is based on the standard ESA on-board data handling concept. This modular system consists of a redundant commande and power distribution unit (CPDU), a redundant control terminal unit (CTU) and a number of remote terminal units (RTU) and mini RTUs. These units are connected to the CTU via a data bus, and access for experiments is via a mini RTU. Since all operations are to be performed in real time, no data memory is required.

The OBDH will provide the following functions:

- accept ground commands with validation and routes routine command via CTU for execution within the appropriate unit;
- acquire sample data from experiments or sub-systems as required;
- formatting and routing of data and housekeeping information to telemetry transmitter;
- a 250 KHz or 1 MHz clock signal together with synchronisation signals for use by the experiments.

A schematic diagram of the sub-system and its interrelations with other spacecraft sub-systems and experiments is shown in Figure 6.2.

### 6.3.4 Telemetry and telecommand sub-system

In view of the observatory nature of the mission, omnidirectional antenna coverage is necessary. This can be achieved by switching between two antennas each providing hemispherical coverage (e.g., EXOSAT); the antennas are mounted on deployed booms. In view of the number of switchings between antennas required during the life of the spacecraft and, in order to minimise the data lost during the change-over time, it is proposed to use PIN diode switches rather than mechanical devices.

Redundant standard 2.5 W RF S-band transponders will be incorporated. The use of 15 m dishes at Villafranca and Carnarvon ensure a down-link margin of 4.3 dB for a telemetry data rate of 30 kb/s. The corresponding telecommand up-link margin would be 18 dB.

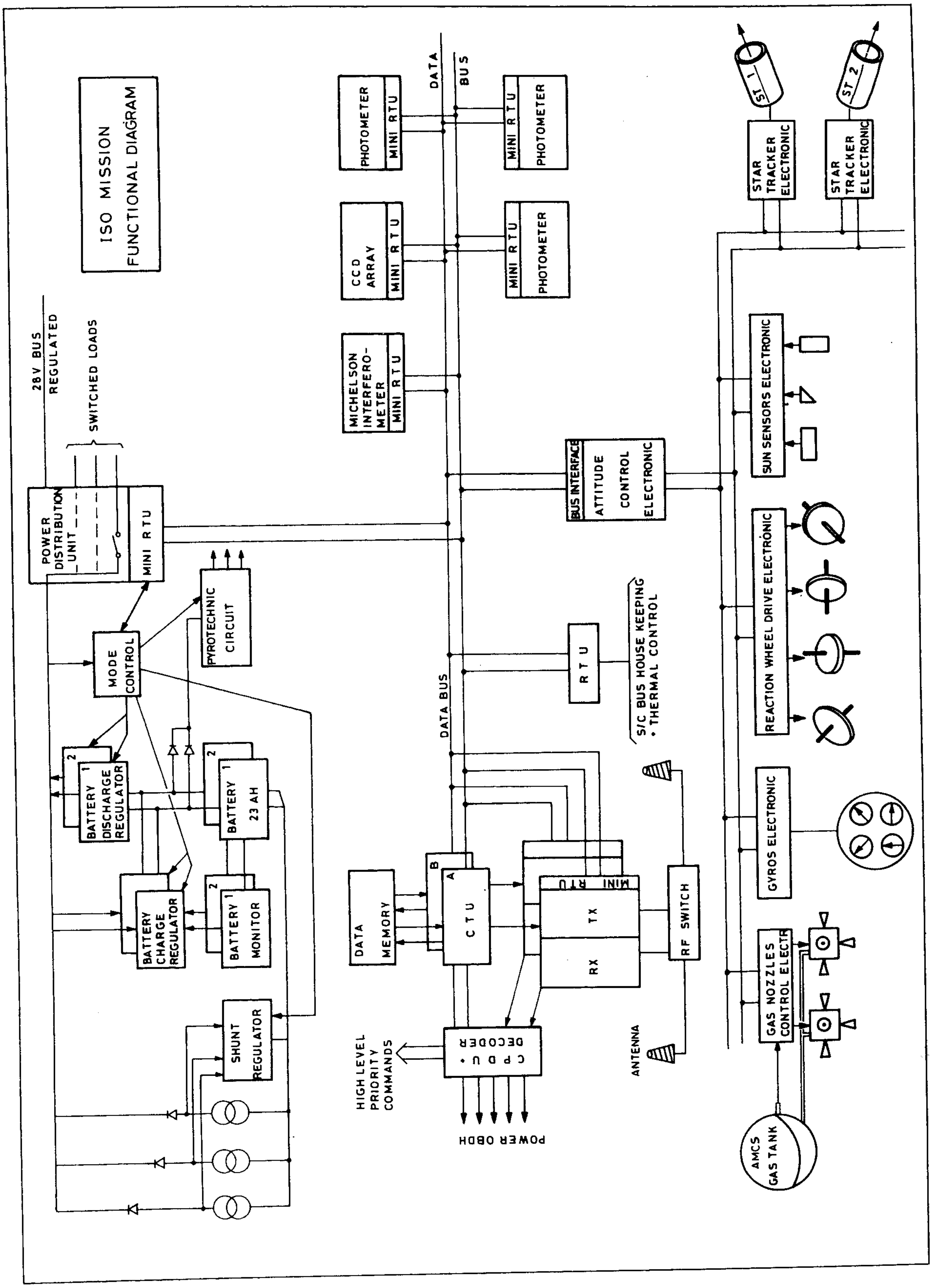

Fig. 6.2 Data Handling Sub-System Schematic

### 6.3.5 The thermal control sub-system

The requirements of the spacecraft thermal control sub-system are:

- to provide to the sub-system equipment compartment a thermal environment which is compatible with the mission operation requirements;
- to minimise the thermal exchange between the equipment compartment and the cryostat;
- to maintain the temperature of the cryostat outer skin as low as possible during the entire mission.

For the sub-system compartment, passive control techniques are suitable; however, a few heaters will be required for temperature maintenance during long eclipses.

Temperature levels will be maintained by a combination of super insulation blankets and adequate radiators on the anti-Sun face. Maximum thermal decoupling of the equipment compartment and cryostat will be a design feature.

With regard to the temperature of the cryostat outer skin, preliminary analysis indicates that a value of about 200 K can be maintained by completely covering the structure with a multilayer insulation blanket.

The Sun-facing side of the cryostat will be shielded by a thermal screen, and low emissivity coatings on all spacecraft surfaces facing the cryostat will be applied. In addition, the cryostat support structure must be manufactured from low conductivity material.

### 6.3.6 Structure

The main structure of the sub-system compartment would be a tube interfacing at one end with the cryostat interface skirt, and at the other end with the launcher. The hydrazine tank would be located inside this central cylinder. The sub-system compartment would be closed by 4 side walls and the upper and lower equipment floors.

This structure is expected to be relatively conventional.

# 7. OPERATIONS AND DATA MANAGEMENT

## 7.1 Introduction

The 12-hour orbit selected for ISO allows for almost continuous coverage of the spacecraft when two ground stations are used. It is proposed that both ground stations are linked to the ESA Operations Control Centre by high speed data links allowing a switch between both stations for data acquisition commanding and tracking.

In the following, the ISO operations are presented based on the preferred concept of an observatory with all the supporting functions (e.g., quick-look and preliminary science analysis) available at one site. This approach is felt to be by far the most attractive in terms of maximum observational efficiency for the scientists. Since the mission lifetime is about 1.5 years, this observational efficiency is considered to be of prime importance. However, it is not the only possible mode of operation. Another option would be to provide quick-look and data analysis facilities at the various institutes that have provided the instrumentation. This, however, would mean sacrificing the near real-time feed back in observations, and it would also probably impair the exchange of ideas between scientists working with the different instruments.

## 7.2 Operations

This section presents a model of the mode and staffing of ISO operations. It assumes that ISO will be controlled from a ground station connected to a real-time data link between the ground station and the satellite (via a second data relay station for part of the day). It draws on the success of the ESA observatory for the IUE satellite modified as necessary to provide round-the-clock operations. It also attempts to improve on this and also on the planning for the EXOSAT observatory operations. Of course, there are alternative modes of operation which are possible and, in the case of photometry, a pre-planned observation programme could be used successfully. On the other hand, there is no doubt that spectroscopy and mapping would greatly benefit from a real time link.

To take advantage of the real time access to the satellite, observers will come to the ISO observatory to perform the fuctions of: (i) identification of targets, (ii) near real time quick-look analysis, (iii) real time optimisation of observing programme, (iv) collection of final outputs within about a day's observation.

Points (i), (iii) and (iv) require little discussion, since they can follow the patterns used successfully by the IUE observatory and at ground-based te-escopes. However, a major improvement over the IUE model can be achieved for point (ii) if the quick-look analysis software forms a natural part of the later image-processing procedures. For example, reconstruction of the spectrum from a Fourier-transform spectrometer should take place during real time and may not need to be duplicated later. Such a software system would have to be well separated from the spacecraft control computer, to avoid interference with operations, and it is proposed that the control and image processing computers be connected only by a one-way link allowing data to be sent to the latter. This also has the possible advantage of permitting a "hands-on" operation of the image processing computer by visiting astronomers without affecting the operations.

## 7.3 Data Management

It is to be expected that, while adequate image processing software should exist for each focal plane instrument at launch, the acquisition of real astronomical data will present problems - and also provide opportunities not previously foreseen. Therefore, it should be anticipated from the start that improvement and optimisation of the image processing software using off-line facilities will be an on-going process following launch through the lifetime of the satellite. A schematic scientific data flow is illustrated in Figure 7.1.

Image processing computers and software support will be necessary to provide:

i) quick-look data in real time
ii) a final image processing system
iii) a test-bed for image processing improvement.

Some of these functions are similar to those required for instrument checkout, where possibly they should be provided as part of the scientific instrument. Mini-computers attached to array processors will probably be adequate for the tasks mentioned above. The exact specification for these computer sustems would only be possible after the experiments are selected and the data processing requirements settled.

Special attention should be paid to the final scientific data reduction activity. While it is proposed that this activity be part of the tasks of the instrument teams which will be selected both for the actual hardware and for the data reduction software (both quick-look and final data processing), it is certainly worthwhile to consider the option that the final processing be actually carried out at the operations centre under the responsibility of the teams but under ESA's overall observatory management. This approach would ensure timely delivery of data products to the user community.

## 7.4 Observatory Staffing

Since it is preferable to concentrate all data reduction activity at the operations control centre, this approach leads to the following requirements.

In order to interface with the users, who will not all be greatly familiar with ISO's performance and capabilities, and to support the improvement of the image processing, a scientific (observatory) group, resident at the ground station, will be necessary following the IUE model.

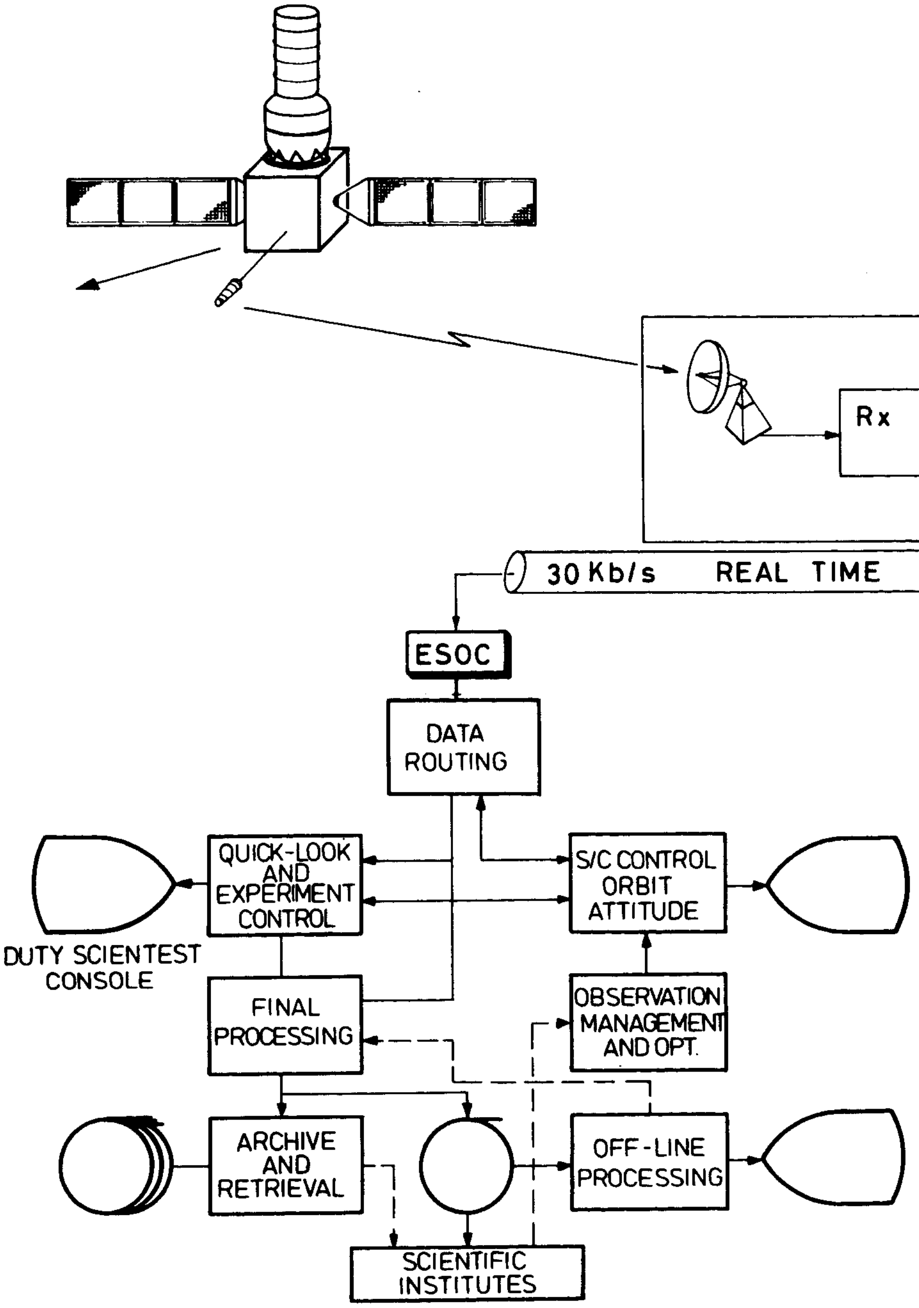

Fig. 7.1 ISO Mission Scientific Data Flow

As a starting point to estimate the number of staff necessary to operate such an observatory, it might be assumed that the following tasks have to be carried out:

(i) to support real time operations
(ii) to "train" new users
(iii) to improve image processing software
(iv) to support image processing.

It is estimated that about 13 man years of effort are required for the basic science operations. Naturally, astronomers performing functions (i), (ii), and possibly (iii), will require time to carry out some research work. Therefore, a figure of roughly 16 man years should be taken as indicative of the level of support required. In addition, about 4 man years of support staff will be essential.

It seems unlikely that ESA alone could provide such a large group of astronomers and analysts to operate the ISO observatory. Apart from this reason, however, it would also make excellent sense to place on the groups providing the focal plane instruments the obligation and the advantage of providing some astronomical and system analysis staff. This would provide an essential and natural continuity between "project" and "operations", given that the instrument groups would be responsible for the image processing software. On the other hand, ESA will need to maintain the overall management of the observations, since it will still bear the major responsibility for all aspects of the operations. A guide to the level of support that might be sought from P.I. groups may be made by considering that there are three focal plane instruments, and for each instrument the P.I. group might provide two astronomers plus possibly one image processing analyst to the ISO observatory.

## 8. MANAGEMENT

The basic philosophy for the division of work is that ESA shall be responsible for the spacecraft systems, spacecraft operations and data handling to the extent proposed in Chapter 7.

Within the definition of the term "spacecraft systems" is included the cryostat and the telescope, but not the scientific focal plane instruments. The latter should be designed, built and tested as single experiments to be integrated in the focal plane package. Each instrument would be the responsibility of a Principal Investigator (PI) who is supported through national funding according to the traditional ESA procedure.

The relationship between the scientific instrumentation for ISO and the spacecraft systems as defined above is rather an unusual one in that the mass of the instruments and, in particular, their power dissipation to the cryogen determine in a major way the total amount of cryogen required, and, hence, the size and mass as well as costs of the single largest component of the spacecraft. This makes it imperative that the design of the total system be correct before proceeding to an advanced stage of development.

This means that it is necessary to identify the type of focal plane instruments and to specify the resource allocations and interfaces prior to the selection of the PIs who will procure the instruments against the fixed specifications.

### 8.1 Proposal Phase

Following approval of the mission by the Science Programme Committee (SPC), ESA will issue an announcement of opportunity for the European scientific community to participate in ISO to provide the specific focal plane instruments and associated equipment against a fixed set of performance specifications. The announcement of opportunity will state the scientific requirements, the technical interfaces and the scheme for their control by ESA, the schedule, deliverable items, responsibilities of the parties, the observation programme philosophy, etc. The proposals from the scientific community must show the management structure within the collaboration and the means for ensuring that the responsibilities for the scientific, technical, operational and analysis activities will be properly discharged.

Selection of proposals will be via the normal route of recommendations by the ESA advisory groups and approval by the SPC.

### 8.2 Design and Development Phase

After the selection, the participating laboratories will be responsible for the detailed design, development, procurement and calibration of the relevant experiment sub-system on a time schedule which is in accord with the development plane (see Figure 8.1). To assist in this process, and to provide the essential very close interaction with the spacecraft design and development process, it will be necessary to establish an ISO Instruments Working Group composed of the experiment PIs, the Project Scientist and an ISO Instruments Coordinator as nucleus, supported by Co-Investigators and the Project Manager, as appropriate.

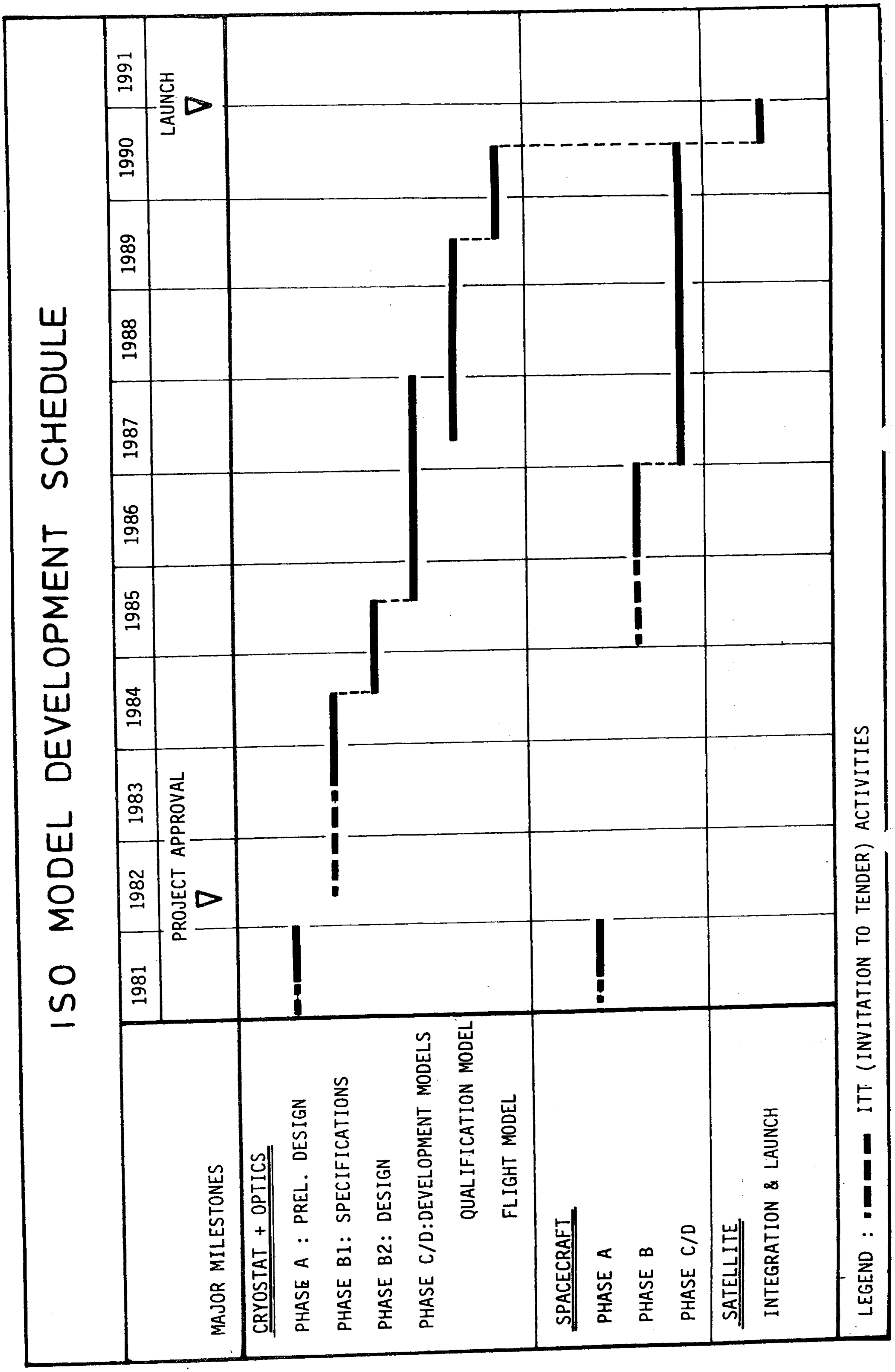
ISO MODEL DEVELOPMENT SCHEDULE
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
MAJOR MILESTONES
PROJECT APPROVAL
LAUNCH
CRYOSTAT + OPTICS
PHASE A : PREL. DESIGN
PHASE B1: SPECIFICATIONS
PHASE B2: DESIGN
PHASE C/D:DEVELOPMENT MODELS
QUALIFICATION MODEL
FLIGHT MODEL
SPACECRAFT
PHASE A
PHASE B
PHASE C/D
SATELLITE
INTEGRATION & LAUNCH
LEGEND : ▪▪▪▪ ITT (INVITATION TO TENDER) ACTIVITIES

Figure 8.1

At an early stage in the Phase B definition of ISO, the ESA Project Manager will draw up an ISO Project Plan. This will provide the blueprint for the future project development through to the operational phase. It will give the necessary visibility to the main elements in the project development and provide an agreed working basis for the project and for the PIs. Those sections related to the instrument development will, of course, be generated in close association with the relevant PIs. The final document will be made available to the ESA advisory and delegate bodies for information.

To minimise the number of changes in the cryostat, it is mandatory that the layout and interface of the telescope and focal plane package be specified and agreed prior to the start of the cryostat design.

For the development and production of the cryostat, it is proposed to build 3 models:

- a structural and thermal development model (STM)
- a qualification model (QM)
- a flight model (SFM).

For the sub-systems, a structural and thermal development model (STM), an electrical engineering model (EM) and a proto flight model (PF) should be sufficient.

## 8.3 Operational phase

At the start of the operational phase, the commissioning, calibration and demonstration of the in-orbit capabilities of the satellite will take an estimated 4 weeks after aperture cover release, during which time the instruments will be used solely by the PI teams.

During the operational phase, the science instrumentation teams are charged with the responsibility for carrying out scientific instrument performance verification, and providing input for updating and fine tuning the science data reduction system.

In general, the observing time on ISO should be assigned to proposers satisfying review by a peer group selection committee. After the commissioning period, the observing time will be appropriately distributed between the PI teams and selected guest observers.