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THE COSMIC BACKGROUND EXPLORER MISSION

Samuel Gulkis, Philip Lubin, Stephan Meyer, and Robert Silverberg

Later this year NASA plans to launch its first dedicated cosmology satellite, the Cosmic Background Explorer (COBE). Its three complementary instruments will make fundamental measurements of the celestial radiation whose origin is believed to stem from processes that occurred at the very dawn of the universe. By measuring the remnant radiation over the entire sky from 1 micrometer to 1 centimeter in wavelength, scientists hope to be able to solve many of the mysteries regarding the origin and evolution of the early universe. The COBE data will address intriguing questions such as what were the conditions at the time when the remnant radiation was emitted? How did the structures we see in the sky today develop? What was the universe like when the first luminous objects formed? Can we see the diffuse radiation from a possible first generation of stars? Was there an era where large amounts of intergalactic dust absorbed much of the early starlight?

The cosmic radiation, created early in the evolution of the universe under drastically different conditions than those present today, probably has several components, each a result of a different stage of the universal evolution and each a result of different processes. The most well established, the Cosmic Microwave Background (CMB), was discovered 25 years ago and the measurement of its properties has been an active area of research since that time. In the infrared spectral region, another component, the Cosmic Infrared Background (CIB), which has not yet been definitively seen, is expected to be the result of the formation of the first objects from primordial material.

Unfortunately, these radiative relics of the early universe are weak and veiled by local astrophysical as well as terrestrial sources of radiation. The different cosmological components may also overlap making the understanding of the diffuse celestial radiation a challenge. Nevertheless, the complimentary COBE instruments with their high sensitivity, wide range of wavelengths, full sky coverage of the observations, freedom from interference by emission the Earth's atmosphere, together with the comprehensive and unified data analysis, will give scientists a consistent and potent means for separating the cosmological signals of interest from each other and from the other non-cosmological radiation sources. Before discussing how the COBE mission will be accomplished, we will review the current state of cosmological theory.

Cosmic History

The discovery of the CMB has led to wide acceptance of the "hot big bang" theory, a remarkable synthesis of a wide range of observational data: the expansion of the universe, the hydrogen-to-helium ratio in the universe, and a natural explanation of the CMB itself. This theory presumes that the universe started from a primeval fireball, an extremely dense and hot tiny volume, that has since expanded to its present scale. As it did so, the matter and radiation cooled from temperatures so hot that the behavior of the primordial "stuff" which existed in the first instant of the universe is beyond the predictive power of today's physics. The cooling initiated events which led to the present universe: neutrons and protons formed from their quark constituents; later, nuclei of helium, tritium and deuterium formed from these protons and neutrons; and as the universe cooled further, neutral atoms formed from the nuclei and the free electrons. The formation of neutral atoms, referred to as the decoupling era by cosmologists, was of critical importance to the development of stars and galaxies because it allowed the matter and radiation to evolve independently for the first time.

(insert Figure 1)

The radiation continued to cool with further expansion and today we observe it as the CMB, whose properties closely resemble that of an ideal thermal source or blackbody at a temperature of 2.7K. Even though it is now so faint and cool, the CMB remains the dominant form of radiant energy in the universe today. Because the matter stopped interacting with the radiation at the decoupling era, the present day radiation gives us a "snapshot" of what the conditions were like when the universe was only about 300,000 years old. Concurrently, the matter could evolve unhindered by radiation pressure and, under the influence of gravity, collapse into the celestial objects we see today. Significant amounts of elements heavier than helium, which are seen in the absorption lines of the oldest stars observed, were probably produced in an even earlier generation of stars formed during this collapse period. The energy from the gravitational collapse and the production of the first heavier elements must have produced a considerable amount of radiation now expected to appear in the infrared. If this picture is correct, a Cosmic Infrared Background (CIB) must exist though it has not yet been detected.

While the general scenario outlined above is supported by existing measurements, it is far from complete. We don't know what the physical conditions were between the first moments of the universe and the formation of the most distant objects we see, a time span of approximately 1 billion years. Was the CMB in thermal equilibrium with the matter at the decoupling era? Is the universe expanding uniformly in all directions? Is the universe rotating? Had galaxies already begun to form at the decoupling era? Answers to these questions are necessary in order to develop a deeper understanding of the present day universe. Fortunately, the study of the CMB and CIB can begin to lead us towards these answers.

Two fundamental properties of the CMB provide clues to the conditions in the early universe: its spectrum and angular variations in brightness. The spectrum refers to the intensity of the radiation as a function of wavelength. Experiments over the past 25 years have shown that the CMB spectrum is approximately that of a blackbody source, telling us that at the time of decoupling, the universe was nearly in a state of thermal equilibrium, an observation which constrains theories of the early universe. Small departures from a blackbody spectrum would imply major energetic processes occurring before the decoupling era which might disrupt the thermal equilibrium, or by matter altering the radiation in the epochs after the decoupling.

(insert Figure 2)

The second important property of the CMB, its angular variation or anisotropy, refers to its brightness in different directions in the sky. Anisotropy in the CMB can be produced by density variations in the matter-radiation composite at the time of decoupling, or by relative motions between the different parts of the universe. Because large scale structures such as galaxies take a long time to form from a uniform distribution of matter, theorists predict that the CMB, strongly coupled to the matter prior to decoupling, will be anisotropic to a small degree. Searches for anisotropy in the CMB which could be attributed to these 'seeds' of present day structures, have been extensive, yet none have been found to a remarkable degree of accuracy. On angular scales of several arc minutes we know that the CMB is smooth to less than 20 parts per million! Assuming that gravity is the only important force driving the evolution of structure on large scales, it is difficult to reconcile this smoothness in the CMB with the lumpiness of the luminous matter which we see today.

One angular variation in the CMB, believed to be associated with the velocity of the Earth with respect to the reference frame of the CMB, has been detected. (insert Figure 3) Along one direction in the sky, the CMB radiation appears warmest and in the opposite direction the coolest. The contrast is minute, being only 0.1 % warmer in the direction of the Earth's motion and 0.1 % cooler in the opposite direction. This form of angular variation is called a dipole distribution because it has two poles, one hot and one cold. The implied velocity of the Earth is about 300 km/sec in the direction of the constellation Virgo. After taking into account the Solar System motion in the Milky Way galaxy, it has been inferred that the galactic center is moving at 600 Km/sec relative to the CMB. This velocity is quite large (0.2% of the speed of light) and it's meaning, although not completely clear, may be related to large scale matter flow in the universe which we discuss below.

Recent Theories of Large Scale Structure

In the past 5-10 years, new ideas have revolutionized the thinking about the evolution of the early universe. The hot big bang model, the central idea a decade ago, while still a good general hypothesis, has been modified and expanded to encompass modern experimental data and ideas.

One of the fundamental difficulties with the big bang model, known as the 'horizon problem', can be resolved with an idea called the inflationary universe. The problem arises in explaining how the temperature of the CMB can be uniform from point to point on large scales. Thermal equilibrium is established by the exchange of energy. In the big bang model, early expansion is so rapid that regions of the sky now separated by more than 2 degrees in angle can never have exchanged energy with each other, even if the energy traveled at the speed of light. Why then do all the parts of the sky appear to have the same temperature? The probability of this being a random occurrence is unimaginably small. The inflationary picture explains the temperature uniformity by postulating that the universe underwent an era of very rapid expansion shortly after its beginning. In this model, the observable universe evolved from a small volume of space that had been in thermal equilibrium prior to the time of inflation. Hence, the CMB is smooth because the CMB photons we see today originated from regions which were once in nearly perfect thermal equilibrium. What we see is therefore only a very small part of a region which had, before the inflation, come to local equilibrium.

A consequence of inflation is that the actual density of the universe is driven to a value called the 'critical density' which implies that the universe contains much more matter than we see as luminous stars and galaxies. The unseen mass could be in the form of cold dark matter, a form of matter which emits no detectable radiation. Inflation would also expand quantum-mechanical density fluctuations which existed in the primordial material before the expansion began. This kind of fluctuation has a well-defined form for its anisotropy. Therefore, a third consequence of inflation is a prediction for how the CMB brightness should vary with angular separation on the sky. The detection of CMB angular fluctuations would be an important test of the validity of the inflationary model.

The extreme uniformity of matter in the early universe, inferred from the isotropy of the CMB, must be reconciled with the condensed structures we see in the present day sky: galaxies, clusters of galaxies, and super clusters. The cold dark matter (insert Figure 4) hypothesis has gained considerable favor in explaining this apparent dilemma. From the point of view of structure evolution, the properties of this cold dark matter are unimportant except that it interact with normal matter only through gravity and that it have velocities, much less than the speed of light.

Incorporation of cold dark matter into the big bang picture has two effects. First, it permits evolution of density perturbations, the seeds for structure formation, before the era of decoupling (see Figure 1). This early formation of structure does not show up in the CMB because the dark matter does not interact with radiation. The normal matter can then fall onto preformed condensations of cold dark matter after decoupling. Second, the overall enhancement of the density in the universe provided by this unseen component increases the rapidity of structure evolution without contradicting evidence from models of nucleosynthesis which appear to limit the total amount of normal matter.

Studies of the distribution and redshift of galaxies have led to surprising conclusions about the density and distribution of luminous matter. Enormous regions of space appear to be virtually free of any galaxies. These regions called "voids", are much larger than one would expect for randomly positioned matter which has clumped gravitationally. The theoretical challenge is to modify the hot big bang picture so that the smooth distribution of the radiation at decoupling, represented by the CMB, and the existence of large voids in the luminous matter distribution can be reconciled. Examples of such modifications to the 'standard hot big bang' range from postulating that small changes in the density cause large changes in the probability of forming galaxies to supposing that cold dark matter, once clumped, can decay causing explosions of truly cosmic proportions which blow the matter out of large volumes and cause the observed voids.

Measured velocity distributions of galaxies, after correcting for the effects of the overall expansion of the universe, also imply the existence of very large scale structure. The velocity distribution measurements are exceedingly difficult and fraught with systematic bias but several independent studies indicate that something unexpected is occurring. Galaxies in large regions of space seem to be moving in unison with velocities which would not be expected from a standard model of the evolution of the matter. It appears that our galaxy is on the edge of an enormous region of space which is moving as though gravitationally attracted towards an object dramatically named the 'great attractor'! The surprisingly large velocity of our Milky Way relative to the CMB, as measured by the dipole CMB variation, may be related to this motion. Both the voids and the large scale motions are experimental evidence which the big bang model, even with the addition of cold dark matter have difficulty encompassing.

The Cosmic Infrared Background.

The questions of how structure evolved from the uniformity of the early universe are also addressed by measuring the properties of radiation emitted after the decoupling era. If matter were as luminous in early epochs as it is today, a measurable CIB would be produced.

There are several pieces of circumstantial evidence for such early luminosity. The oldest stars observed are known to contain significant amounts of elements heavier than helium which can only be formed by nuclear fusion in stellar interiors. Since the heavy elements produced in stellar interiors do not become detectable until they are ejected into the interstellar medium by a star's death, the observed heavy elements in oldest stars must have been created in an earlier generation of stars. It is likely therefore, that the oldest stars we see are at least a second generation. Where is the light from the first generation of stars? Were these first stars smoothly distributed in space or clumped together to form the first galaxies? If clumped, the radiation might be found in highly redshifted protogalaxies and would appear as extended dim patches in the sky. If the stars formed earlier than larger scale structure then most of this light could only be detected as a diffuse uniform 'glow' in all directions on the sky.

It is possible that after the production of the heavy elements some of the ejected material medium precipitated into small particles or dust. This dust would have the effect of absorbing the radiation from the first generation stars. The dust would heat up, and re-radiate the energy at longer wavelengths. The effect of such a process is to make the energy from the early heavy-element-producing stars appear in the far infrared and, if the density of the dust were large enough, wash out the angular structure in the infrared background.

The COBE Satellite

It is evident that many new and exciting ideas about the formation and early development of the universe have been put forward, and that detailed and comprehensive observations of the cosmological background radiation are the key elements needed for sorting out these ideas. The faintness of the cosmological background relative to the astrophysical and terrestrial foreground conspire to make these observations extremely difficult to obtain using ground-, aircraft-, balloon-, and rocket-based experiments.

The collective experience gained from the sub-orbital observations argues strongly for performing observations of the cosmic background radiation from an Earth-orbiting satellite. Properly shielded from the Sun and Earth and oriented to provide full sky coverage, a satellite can make measurements over a broad frequency range and over the entire sky, not only to understand the cosmological background, but also to measure the local astrophysical sources of radiation.

Astrophysical sources of radiation, rather than instrument sensitivity, set the ultimate limits on the ability to measure the cosmological background. The dominant foreground astrophysical sources (Figure 6) include dust in our solar system, synchrotron radiation from electrons losing energy in galactic magnetic fields, thermal radiation from interstellar dust in our own galaxy, and the integrated emission from the stars and external galaxies. Because the different sources are distinguishable using their spatial and spectral characteristics, it is possible to separate the foreground sources from the cosmological backgrounds. Well calibrated, multi-frequency, full sky maps are required to perform this separation.

The COBE satellite was designed and built specifically to fill the need for an orbiting platform to measure the CMB and CIB with a limiting sensitivity set by the astrophysical foreground sources. It has the capability to measure the celestial background radiation over the entire sky, from the near infrared to centimeter wavelengths. Primary mission objectives are to search for angular anisotropies in the CMB, to measure the spectrum of the CMB, and to search for and measure the diffuse CIB emission. Understanding emission from the foreground astrophysical sources is also a mission objective because of its intrinsic importance to understanding our Solar System and Galaxy, and because the cosmological background cannot be determined without this knowledge. The broad range of spectral coverage, the full sky coverage, the overall attention to the reduction of systematic errors in the design and construction of the spacecraft, instruments, and the spacecraft orbit, all combine to provide the COBE mission with a unique capability for measuring the diffuse background emission from the sky.

COBE carries three complimentary scientific instruments: a set of differential microwave radiometers, a polarizing Michelson interferometric spectrometer, and an infrared filter photometer. Each instrument measures a different aspect of the cosmological background radiation. The Differential Microwave Radiometers (DMR) will measure the large scale anisotropy in the CMB to better than one part in a hundred thousand. Data from this instrument will be used to search for the "seeds" of the present large scale structures in the universe, anisotropic expansion or rotation of the universe, gravity waves, cosmic strings, or large scale matter flows. The Michelson interferometric spectrometer or Far Infrared Absolute Spectrophotometer (FIRAS) will measure the spectrum of the background radiation from 1 centimeter to 100 micrometers for each of 1000 different parts of the sky. Deviations of the spectrum from that of a blackbody will be measured to an accuracy of one part in a thousand. A detected deviation would indicate the presence of very energetic sources in the early universe. For example, it may be possible to measure the spectral distortion produced by the recombination of hydrogen during the era of decoupling. This would give scientists important data about the universe when it was only 300,000 years old. Inverse Compton scattering of cosmic background photons by hot electrons produces a well known perturbation of a blackbody spectrum, and its detection would indicate the presence of a hot ionized gas produced by the energy injection well after the era of decoupling. Such heating could have been produced by star or galaxy formation in which case the time of heating could be related to the birth of the first stars and galaxies. The third instrument, the Diffuse Infrared Background Experiment (DIRBE) will measure the absolute sky brightness in 10 bands at wavelengths ranging from 1 to 300 micrometers. This instrument will perform the most sensitive search yet undertaken for the diffuse infrared light from the early universe, light from the first generation of protogalaxies, galaxies and stars. The spectral range of the emission will indicate the nature of the processes responsible for the emission as well as the presence of astrophysical dust. DIRBE will also make important measurements of the emission from foreground sources such as interstellar and interplanetary dust, galactic starlight, IR galaxies, quasars, and galaxy clusters. Table I summarizes the principal features of each instrument.

The three instruments on COBE have each been designed to minimize systematic errors and to provide the sensitivity needed for the measurements of the cosmological backgrounds. The distinguishing feature of the DMR instrument which allows it to measure exceedingly small variations in the background radiation is its capability to measure power differences (hence the name Differential Microwave Radiometer) rather than total power. Sensitive direct measurements, of power are difficult because of ever present small changes of receiver gain. The DMR instrument avoids this problem by rapidly switching between two nearly identical horn-type antennas, each aimed 30 degrees from the spacecraft spin axis. The measured power differences are converted to temperature differences in the sky using onboard calibration sources and measurements of the moon as references.

The DMR instrument is constructed as three separate but functionally similar receiver boxes, one for each of the three wavelengths. The specific wavelengths were chosen to optimize the capability to distinguish between local galactic and dust emission and the CMB. The horn-type antennas used on the DMR are designed to reject almost completely the off-axis radiation coming from the Earth and Sun. To provide high sensitivity, critical components of the two shorter wavelength radiometers are passively cooled by radiation to about 140 K, while the longest wavelength radiometers operate near room temperature. The cooled radiometers are able to detect a temperature difference of about 0.025 K in a one second measurement while the room temperature radiometers are about a factor of two less sensitive. The sensitivity of the data from each DMR receiver after one year of observation will be about 100 microKelvin (.0001 K) per field-of-view on the sky, approximately 7 times the sensitivity of the 3 millimeter map shown in Figure 3. By combining these individual points, it will be possible to measure temperature variations over the whole sky as small as 10 microKelvin, about three parts in a million of the CMB or 300 times smaller than the amplitude of the confirmed dipole variation mentioned earlier. Even the dipole temperature difference due to the motion of the Earth around the Sun with respect to the CMB, about 270 microKelvin, will appear as a large signal relative to the noise!

The FIRAS instrument, like the DMR, is a differential instrument. It measures the difference between the spectral power received from the sky and an internal reference source with a controllable temperature and calibrated emission properties. The high accuracy of the FIRAS instrument is attributable to the use of a calibration source which may be placed in the throat of the input horn. The spectrum emitted by the calibrator is within 0.01% of a blackbody. By adjusting the temperature of the calibrator to nearly match the sky flux, the spectrum of the sky can be directly compared to that of a blackbody with little demand on the instrument. Thus only the difference between the sky variation and the ideal spectrum is measured. Instrumental effects which often lead to systematic errors are minimized in this way.

The FIRAS instrument is a polarizing Michelson interferometer. This design has the advantage of minimizing the effects of detection noise by measuring all wavelengths with one detector element simultaneously. Radiation from the sky enters the instrument through a trumpet-shaped cone antenna which suppresses the off-axis radiation. The spectrum of the incoming radiation is deduced using the phenomena of wave interference. Two moving mirrors vary the difference in the length of two paths taken by the radiation after it is divided by a polarizing beamsplitter. On recombining, the radiation alternately constructively and destructively interferes with itself giving information on the its spectral content. FIRAS is sensitive over a wavelength range from 10 to 0.1 millimeters. The instrument field of view is 7 degrees directed along the spacecraft spin axis.

FIRAS is designed to measure the deviation of the CMB spectrum from that of a thermal source. This information will help determine the conditions of the universe at the time of decoupling as well as putting limits on diffuse emission over its whole sensitivity range. In the regions near the celestial poles the FIRAS instrument, because it views this area on each orbit throughout the entire year, will also be able to search for angular variation in the CMB and any other sources to very high sensitivity.

The DIRBE instrument is distinguished by its optics, designed with special attention being paid to the elimination of stray light from off-axis sources, as well as from the emission from the spacecraft and instrument itself. A system of light baffles, radiation stops and an extremely clean highly-polished mirrors ensure a very small radiation contribution from sources outside the desired beam. The instrument will be able to measure small residual background radiation with a sensitivity of about 1 percent of the foreground emission. The basic instrument design is that of an unobscured off-axis Gregorian telescope with a primary mirror of 20 centimeters and a field of view of 0.7 x 0.7 degrees. The telescope is pointed 30 degrees away from the satellite spin axis so that the rotation varies the angle between the DIRBE field-of-view and the Sun. A device resembling a tuning fork interrupts the beam 32 time a second to constantly compare the incoming radiation to the near zero light level of a cold reference surface interior to the instrument. Ten spectral channels observe the same field simultaneously to cover the spectrum from 1 to 300 micrometers.

The three shortest wavelength bands are polarization sensitive, and are ideal for characterizing the sunlight scattered from the interplanetary dust. The four middle bands are dominated by the thermal emission of the interplanetary dust and will provide unprecedented sensitivity to diffuse emission from an early generation of stars. The longest wavelength channels will search, to high sensitivity for radiation which may have been reradiated from intergalactic dust produced from this early generation of stars.

Each of the 10 DIRBE channels will measure the absolute flux from the sky (a unique aspect of DIRBE in this spectral region) permitting the search for diffuse emission. DIRBE has the spectral coverage and sensitivity which will enable the separation of planetary and galactic dust emission from the cosmologically interesting sources. The questions related to the emission of radiation from an early generation of stars or larger structures, and whether intergalactic dust has since absorbed and re-emitted this radiation, are uniquely suited to scrutiny with the DIRBE data.

In addition to the three instruments, the satellite's other components are the large cryogenic dewar, the deployable radiation shield, and the attitude control system. The purpose of the shield is to protect the sensitive instruments and cryogenics from solar and terrestrial thermal radiation, and from radio frequency interference. The DIRBE and FIRAS instruments are located inside the dewar to maintain them at a temperature less than 2 K. This is necessary in order to minimize radiation from the instruments themselves and to permit the use of sensitive detectors. The dewar contains enough superfluid helium to keep the instruments cold for about one year, the nominal mission lifetime. One year is needed to achieve the required sensitivity and full sky coverage. The DMR and some of the DIRBE detectors can remain functional without the need for cryogens, thereby offering the possibility of additional observations beyond the nominal lifetime. The DMR instrument is located around the outside of the dewar also protected by the radiation shield. Solar arrays supply electrical power to the satellite except during short eclipse periods which occur during only part of the year when batteries will be used. The entire satellite, comparable in size and weight to that of a large automobile, will be lifted into orbit using a Delta vehicle, launched from the Western Space and Missile Center in California.

The COBE orbit allows the three scientific instruments to scan the entire sky, while at the same time keeping them in a stable thermal environment and with minimal interference from the Sun and Earth. It is a nearly polar, circular orbit at 900 km altitude, arranged to remain near the day-night terminator. It is called a Sun-synchronous orbit because precession caused by the pull of the Earth's equatorial bulge maintains the orbit plane nearly perpendicular to the sunlight throughout the year. The attitude control system keeps the instrument's view directions aligned about 90 degrees from the Sun and 180 degrees from the Earth as shown in Figure 8. The entire spacecraft rotates at 0.8 revolutions per minute. The rotation produces a scan pattern that serves to reduce systematic errors in the DMR and provides DIRBE with a range of solar illumination view angles to view the interplanetary dust particles. As the brightness of the interplanetary dust particles depends strongly on the ecliptic latitude and the Sun illumination angle, these particles will be easy to recognize and subtract from the background measurements. The rotation also produces a uniform heating of the satellite by the Sun thereby reducing temperature gradients within the satellite which are a potential source of systematic errors for the sensitive instruments.

The COBE LEGACY

With the data taken with these three instruments, the COBE mission will produce a set of fundamental information of unprecedented scope and accuracy. The final output of the mission will be full sky maps spanning four orders of magnitude in wavelength. Two series of results will be published and delivered to the National Space Science Data Center within three years of launch. The first is a set of maps which are calibrated and corrected for all known instrumental and spacecraft effects. The second will include fitted models of local astrophysical sources and maps in which all known sources of foreground emission have been removed leaving only the cosmological components, the CMB and CIB radiation.

The data resulting from COBE will answer many outstanding questions about the early history of the universe. Some of these questions have been asked for centuries, while others have arisen more recently as a result of new experiments and ideas. We can expect that the already active field of cosmology will make a leap forward because of new COBE discoveries.

In the long run, however, it is the comprehensive data set which will be the greatest contribution of the COBE mission. The value of the data will be vastly greater than the sum of the individual measurements or results from anyone instrument. The uniformity of the analysis, the ability of each instrument to confirm and cross-check the results of the others, and the sheer breadth and completeness of the information will lead to a level of reliability which would not be achievable in a mission of lesser proportion. Future cosmological investigations of the early universe and large-scale structure, theoretical and experimental, in whatever direction the field progresses, will refer heavily to this COBE legacy.

BIBLIOGRAPHY

VERY LARGE STRUCTURES IN THE UNIVERSE. J. Burns in *Sci. American,* Vol. 255, No. 1; pages 30-39, July, 1986.

*THE LARGE SCALE STREAMING OF GALAXIES. A. Dressler in.*Sci. American,*Vol. 257, No. 3; pages 46-54, September 1987.

*SUPERSTRINGS, M. Green in *Sci. American,* Vol. 255, No. 3, pages 44-56, September, 1986.

*THE INFLATIONARY UNIVERSE. A.H.Guth and P.J.Steinhardt, in *Sci. American,* Vol. 250, No. 5; pages 116-128, May, 1984.

*DARK MATTER IN THE UNIVERSE. L. M. Krauss in *Sci. American,* Vol. 255, No. 6, pages 50-60, December 1986.

THE COSMIC BACKGROUND RADIATION AND THE NEW EITHER DRIFT. R. A. Muller, in *Sci. American,*Vol 238, No. 5, pages 64-74, May 1978.

THE LARGE SCALE STRUCTURE OF THE UNIVERSE. J. Silk, , A. S. Szalay and Y. B. Zel'Dovich in *Sci. American,* Vol.xx; pages October 1983.

*THE BIG BANG. J. Silk. W. H. Freeman and Company, New York, 1989.

References marked with an '*' are highest priority.

FIGURE CAPTIONS

FIGURE 1 The radius of the observable universe according to the standard big bang model and the inflationary model(adapted from Guth and Steinhardt) are shown on the left. The right hand side of the figure shows an expanded time scale covering the time from the decoupling era to the present. The figure indicates the time at which the CMB decoupled from the matter and the expected period in which a cosmic infrared background(CIB) might have formed. The CMB may contain evidence about the distribution of matter at the period of decoupling. It can be noted that protogalaxy formation, primeval galaxies, and the first starts probably formed beyond the most distant quasars observed. COBE will address cosmological questions related to events that occurred during the first several billion years since the time of the big bang.

FIGURE 2 The observed intensity of the background radiations at any frequency can be characterized in terms of the temperature of a blackbody or thermal source. In panel A of this figure we plot the equivalent thermal source temperature of the CBR implied by some different models for the early universe. A perfect thermal source appears as a straight line at the source temperature. A large energy release just prior to or very near the decoupling era might not leave sufficient time for the universe to come back into complete thermal equilibrium(curves a and b). A model in which the effects of cosmic strings are included is also shown (curve c).

In the second panel of the figure we show the CMB in a different format. The plot represents the energy content of the radiation versus wavelength. We also show some estimates of where the energy which might be produced by a)exploding early stars, b) black holes, and c) primeval galaxies would appear if no astrophysical dust were present in the early universe. Since some dust is almost certainly present in the early universe, the energy from such source would be shifted into the wavelength region where COBE's FIRAS and DIRBE may be able to uncover these fossils.

FIGURE 3 A nearly complete map of the sky is shown made at a wavelength of 3 mm. The map clearly shows the effect of the Earths motion relative to the CBR. This so-called "dipole" anisotropy is analogous to the Doppler shift of sound waves familiar from passing cars and trains sounding their horns. The CBR appears slightly warmer (red) by 0.003 K in the direction of the Earths motion and slightly cooler (blue) by 0.003 K in the opposite direction. We are moving towards the constellation of Leo and away from the Aquarius. The velocity of the Earth relative to the CBR from this and other data is about 300 Km/sec or 1 million miles per hour. This corresponds to 0.1% of the speed of light. The map is a projection of the whole sky onto a plane surface analogous to maps of the Earth. The top and bottom correspond to the north and south celestial) poles with the horizontal centerline corresponding to the (celestial) equator. The center(red) of the map corresponds to the direction of our motion approximately towards Leo. This map was made by Lubin et al (1984) from a balloon-borne radiometer which served as a prototype for the COBE DMR detectors.

FIGURE 4 The Growth of Structure at the Time of Decoupling.The growth of variation in density is highly enhanced immediately after the decoupling event (colored region) due to the effect of previously formed structure in the cold dark matter (line marked cold dark matter) as shown by the curve labeled normal matter. In the absence of cold dark matter the normal matter would not experience such a large growth of density fluctuations, rather, it would follow a slower growth (dashed line).

FIGURE 5 Figure shows measurements of the galactic radiation obtained with the IRAS satellite.Similar maps will be made from the COBE data and used to subtract the galactic emission from the CBR. After the sources of non-cosmological radiation are accounted , the residual radiation will be examined for evidence for the glow from early stars and galaxies.

FIGURE 6 This graph shows the expected brightness that the COBE experiments will observe. For some of the non-cosmological sources the brightness varies on the sky, and an approximate minimum brightness is shown in the figure. A model for the emission of the first stars (black) and primeval galaxies (orange) is shown. Also shown on the graph are the CMB(blue), the emission from interstellar electrons (green), the thermal emission of warm microscopic interstellar dust grains in our Galaxy, and the emission and scattered light from dust grains in the solar system.Estimated sensitivity limits of the three COBE experiments are also indicated. Note that there are two wavelength regions where the light of cosmological origin is expected to dominate "local" sources.

FIGURE 7 The figure shows an artist's conception of the COBE satellite in orbit above the Earth. The locations of the three experiments are shown as well as the major functional components: the deployable solar panels, the communications antennas, some pointing system components and the thermal and radiation shield. The top of the cryogenic dewar containing the supply of liquid helium is also indicated. The COBE satellite weighs 5000 lb at launch. It is 19 feet long and 13 feet in diameter with its shield deployed, comparable in size to a large automobile.

FIGURE 8 This schematic diagram of the COBE orbit shows how it passes near the Earth's poles at the terminator between night and day. The orbit is specially chosen so that as the Earth revolves about the Sun during the one year mission lifetime, the plane of COBE's orbit remains nearly perpendicular to the direction of the Sun light as shown. To avoid radiation from the Sun and Earth, the spin axis of the satellite is pointed almost perpendicular to the direction of the Sun-Earth line and almost straight out from the Earth.

FIGURE 9 DIFFERENTIAL MICROWAVE RADIOMETER for measuring the anisotropy of the cosmic background radiation is shown schematically in this diagram.The two corrugated horn antennas point at different parts of the sky, and are alternately connected to the receiver by the switch 100 times per second. The signal entering the receiver is translated to a lower frequency, amplified, and detected. The synchronous demodulator reports the difference in power received in the two antennas. Six instruments with this design, operating at three wavelengths (3.3, 5.7, and 9.6 mm) comprise the DMR instrument.

FIGURE 10 FIRAS INSTRUMENT FOR MEASURING THE CBR SPECTRUM is shown schematically in this figure. The trumpet shaped cone collects light from the sky and funnels it to a beam splitter which divides the radiation into two components as shown by the (red and green) wavy lines. The two components reflect from movable mirrors that redirect the radiation back to the beam splitter, which then recombines the two beams at each of two detectors. The two beams will recombine perfectly if the delay between the two beams is an integral number of wavelengths, but will cancel if the path difference is an odd number of half wavelengths. The is intensity at each wavelength is measured by varying the position of the movable

FIGURE 11 This diagram shows the optical concept of the DIRBE. Light from the sky is collected by the unobscured primary mirror and is focused through stray light stops to ensure that only light from the sky is analyzed by the instrument. After passing through or being reflected from the vibrating beam interrupter, the light passes through various wavelength dependent reflectors, and onto the detectors, each of which has a filter or filter polarizer combination to define the wavelength and polarization of the light being measured.

TABLE I

INSTRUMENT PARAMETERS AND SCIENCE TEAM MEMBERS				
Parameter	DIRBE		DMR	FIRAS
Wavelength	1.1-1.4 2.0-2.4 3.0-4.0 4.5-5.1 8-15 (in micrometers)	15-30 40-80 80-120 120-200 200-300	3.3, 5.7, and 9.6 mm	0.10-10 mm
Spectral resolution	shown above	1 GHz	$0.2\ cm^{-1}$	
Field of view	0.7 deg square	7 deg diameter	7 deg diameter	
Type	Filter photometer		Dicke switched differential radiometers	Fourier transform polarizing interferometer
Flux Collector	Off-axis Gregorian telescope		Corrugated horns separated by 60 deg	Smooth flared horn
Sensitivity (in field of view)	10^{-13} W/sq cm	.0001 K	$<10^{-13}$ W/sq cm (3.3 and 5.7 mm) .00025 K (9.6 mm) (after 1 year)	(0.5 to 5 mm)
Line of sight	30 deg off spin axis		30 deg off spin axis	Spin axis
Detector	Photovoltaics for <5.1 photoconductors for 8-120 bolometers for 120-300		Diode Mixer	Bolometers (4)
Calibration	internal reference celestial sources	noise diode moon	blackbody with temperature	controlled to within .001 K
Data rate(bits/sec)	1713		216	1330

COBE Science Team Members: Charles L. Bennett(1), Nancy W. Boggess(1), Edward S. Cheng(2), Eli Dwek(1), Samuel Gulkis(3), Michael G.Hauser(1)(Principal Investigator for DIRBE Instrument), Michael Janssen(3),Thomas Kelsall(1), Phillip M. Lubin(4), John C. Mather(1),(COBE Project Scientist and Principal Investigator for FIRAS Instrument) Stephen S. (2), S. Harvey Moseley(1), Thomas L. Murdock(5), Richard A. Shafer(1), Robert F. Silverberg(1), George F. Smoot(6)(Principal Investigator for DMR Instrument), Rainer Weiss(2)(Chairman of the COBE Science Group), David T.Wilkinson(7), Edward L. Wright(8)

(1) Goddard Space Flight Center; (2)Massachusetts Institute of Technology;
(3) Jet Propulsion Laboratory; (4)University of California at Santa Barbara;
(5) General Research Corporation; (6)University of California at Berkeley;
(7) Princeton University; (8)University of California, Los Angeles

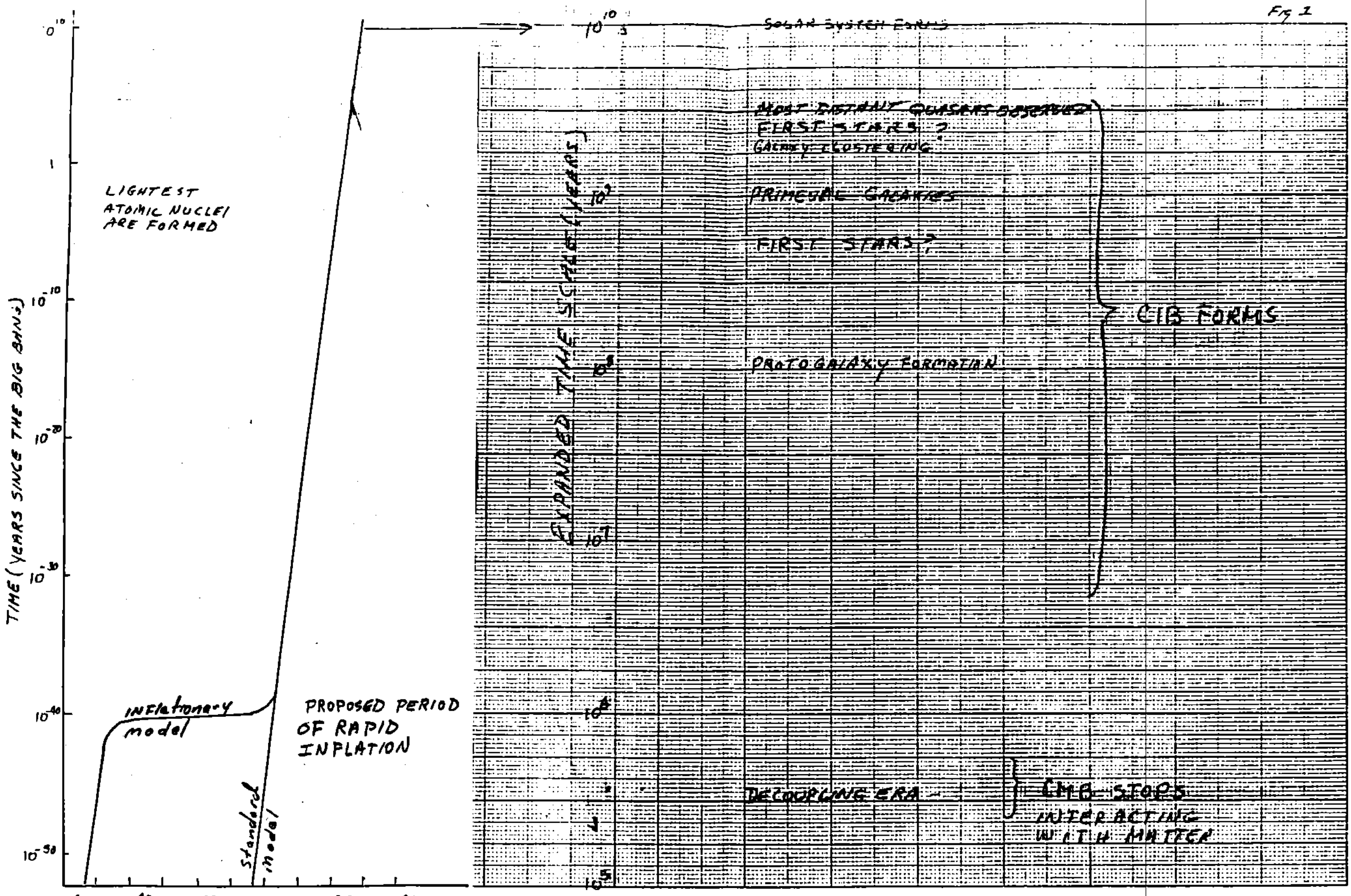


Fig 1
Gulkis, Lubin, Meyer, Silverberg

ST PANEL—FIG 2

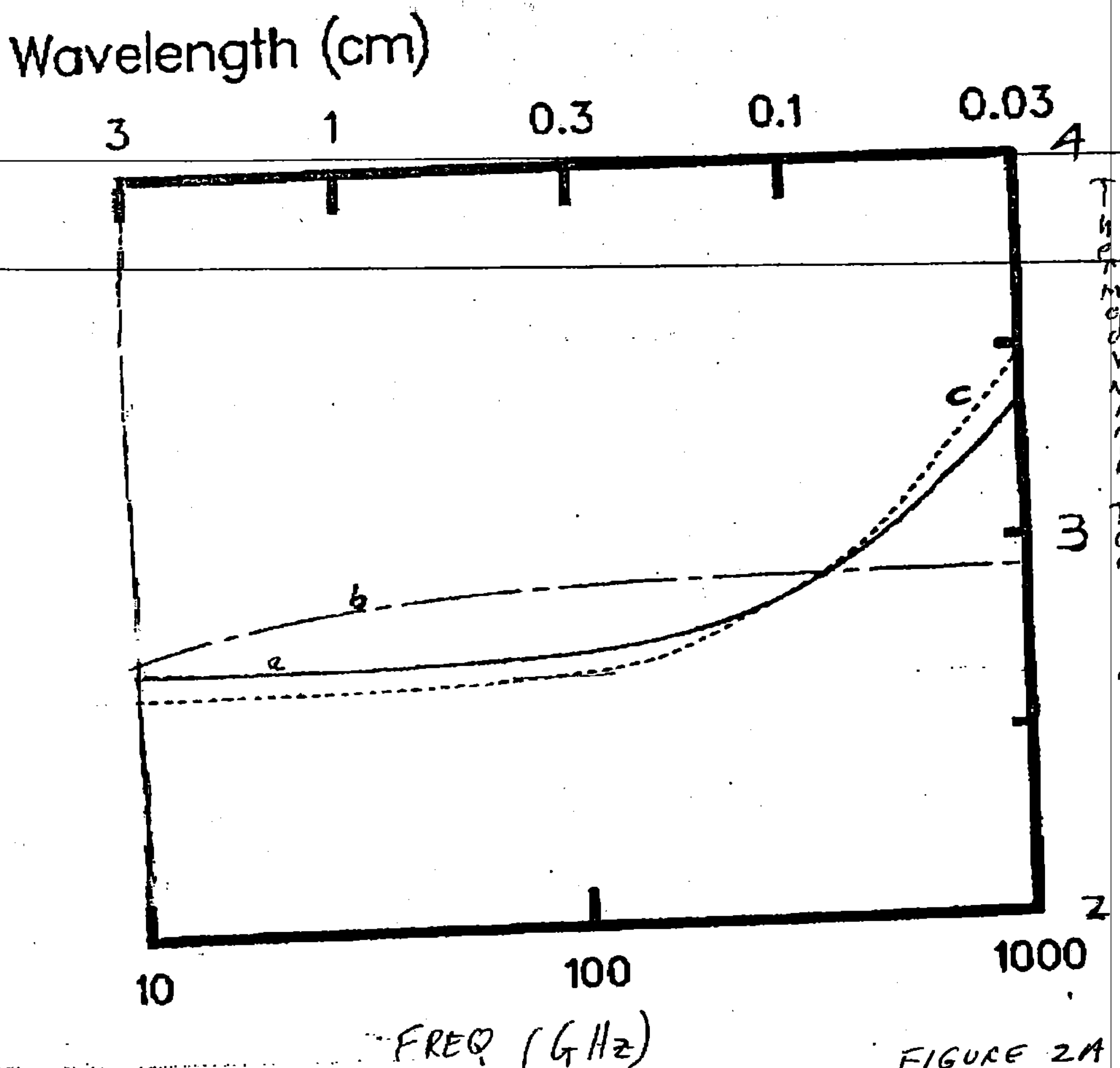


FIGURE 2A

GULKIS, LUBIN, MEYER, SILVERBERG

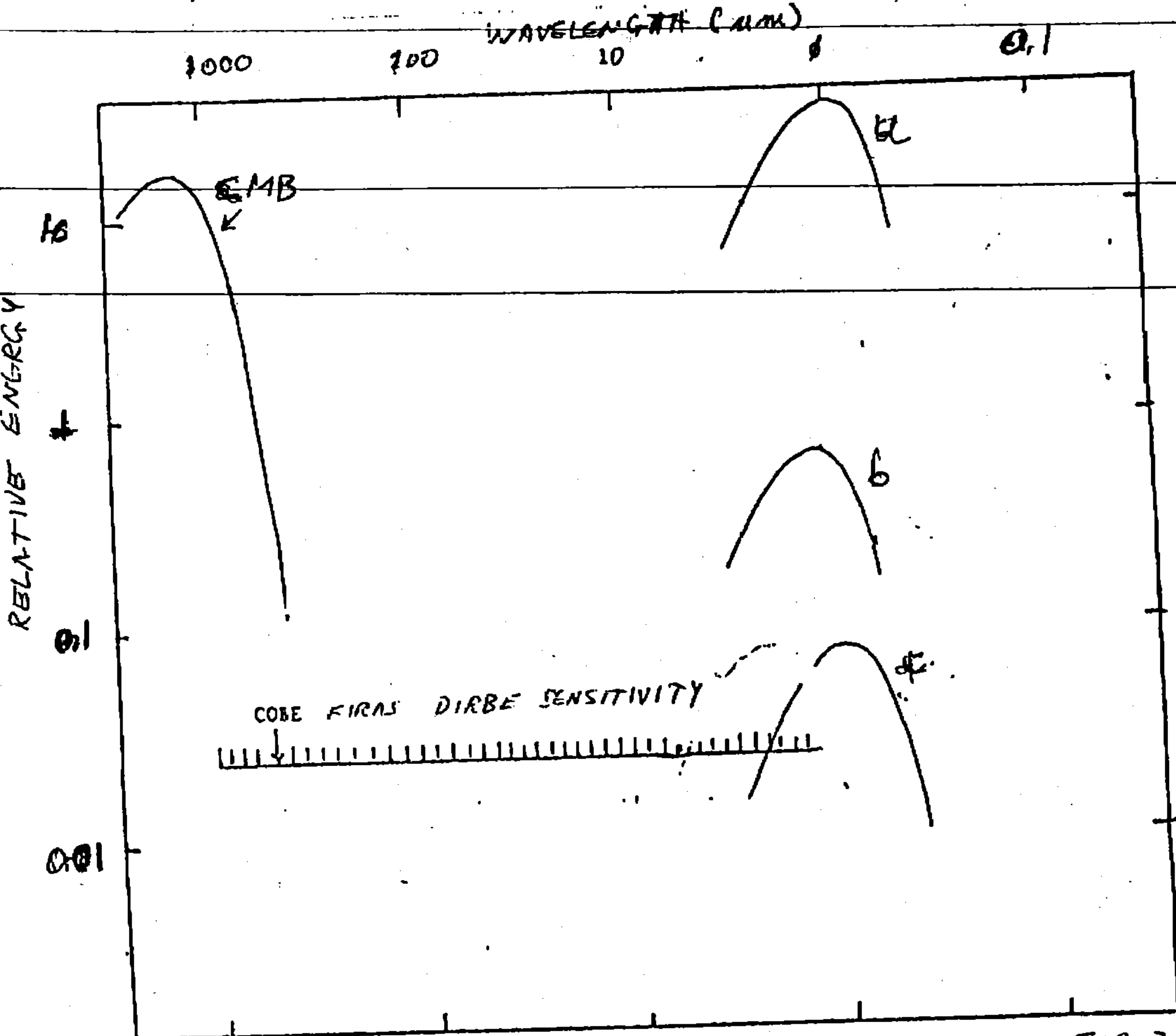


FIG 2B

GULKIS, LUBIN, MEYER, SILVERB

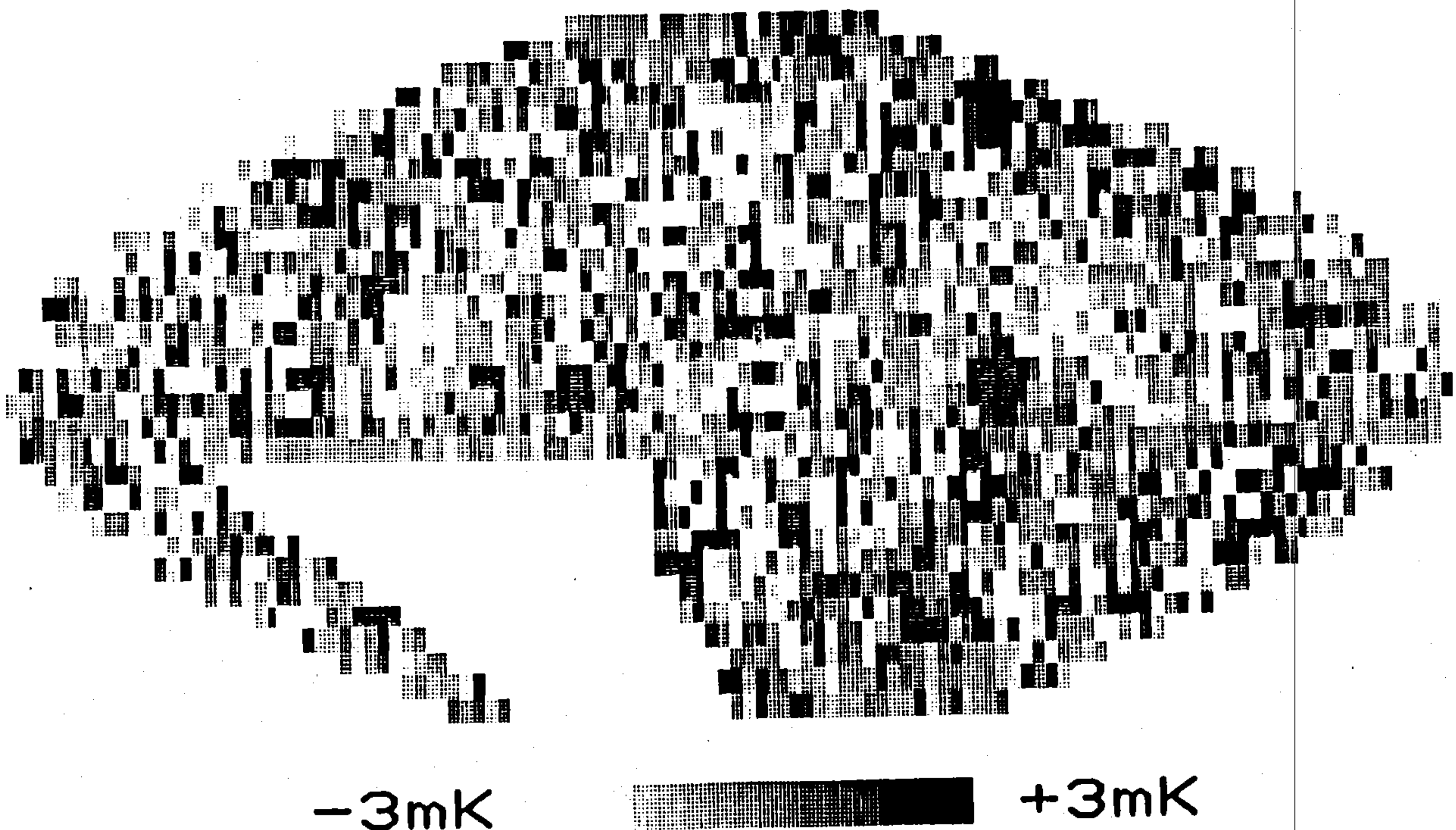


Figure 3

GULKIS, LUBIN, MEYER, SILVERBERG [illegible]

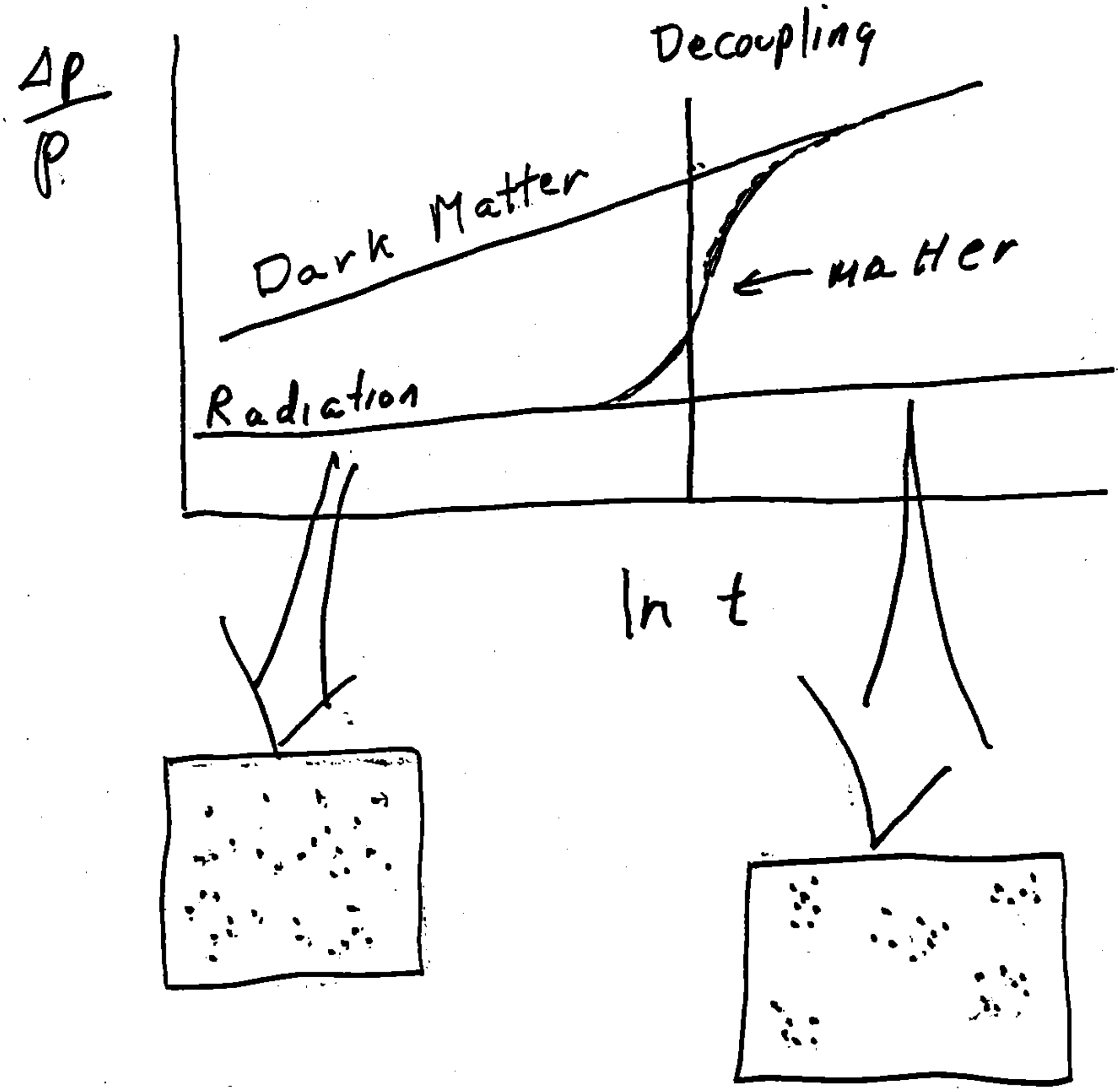
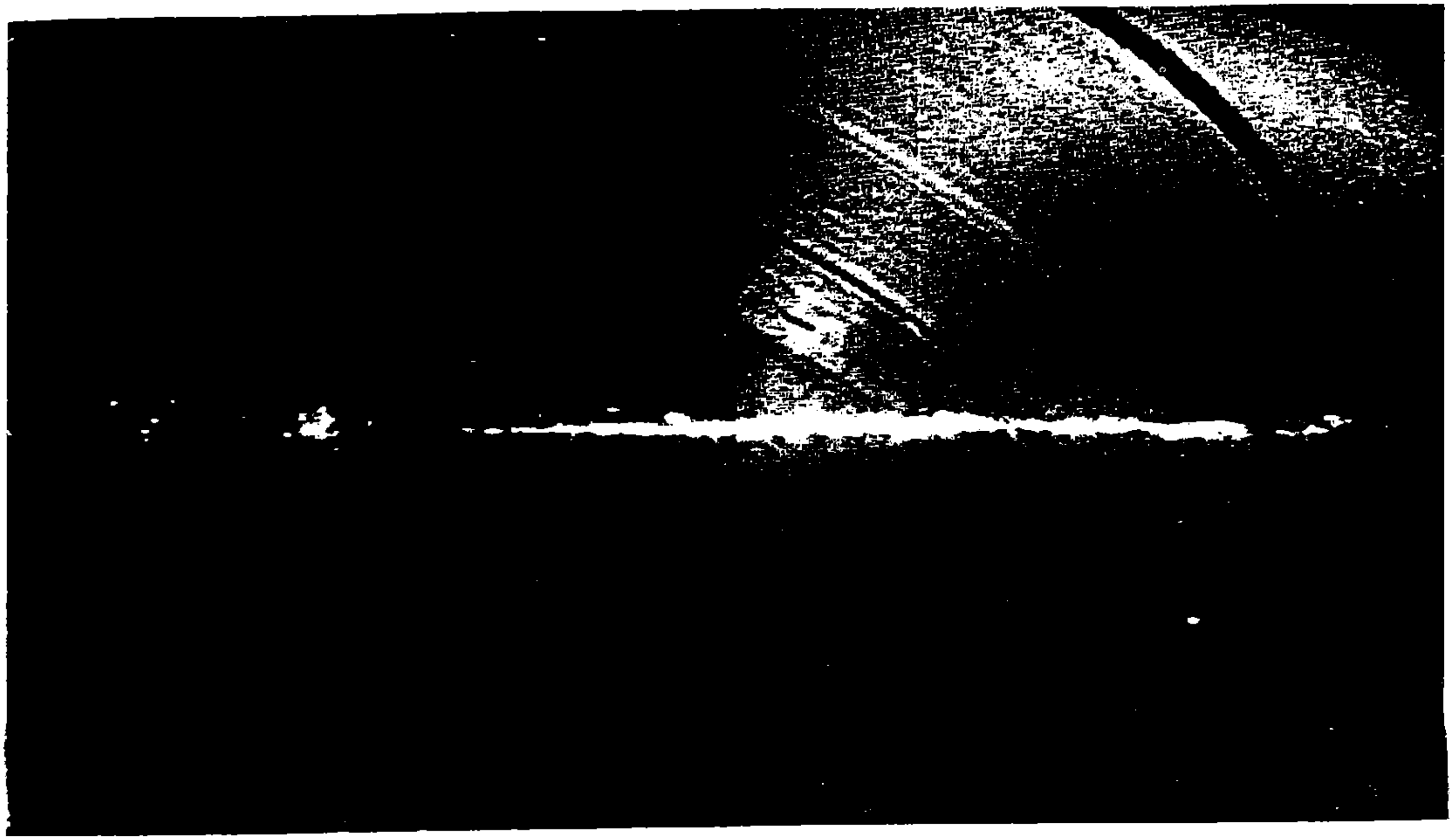


Fig 4

GULKIS, LUBIN, MEYER, SILVER

JPL

Color photograph to be provided by S. Gulkis



All-sky infrared map made from IRAS data.

Fig 5

Gulkis, Lubin, Meyer, Silverberg

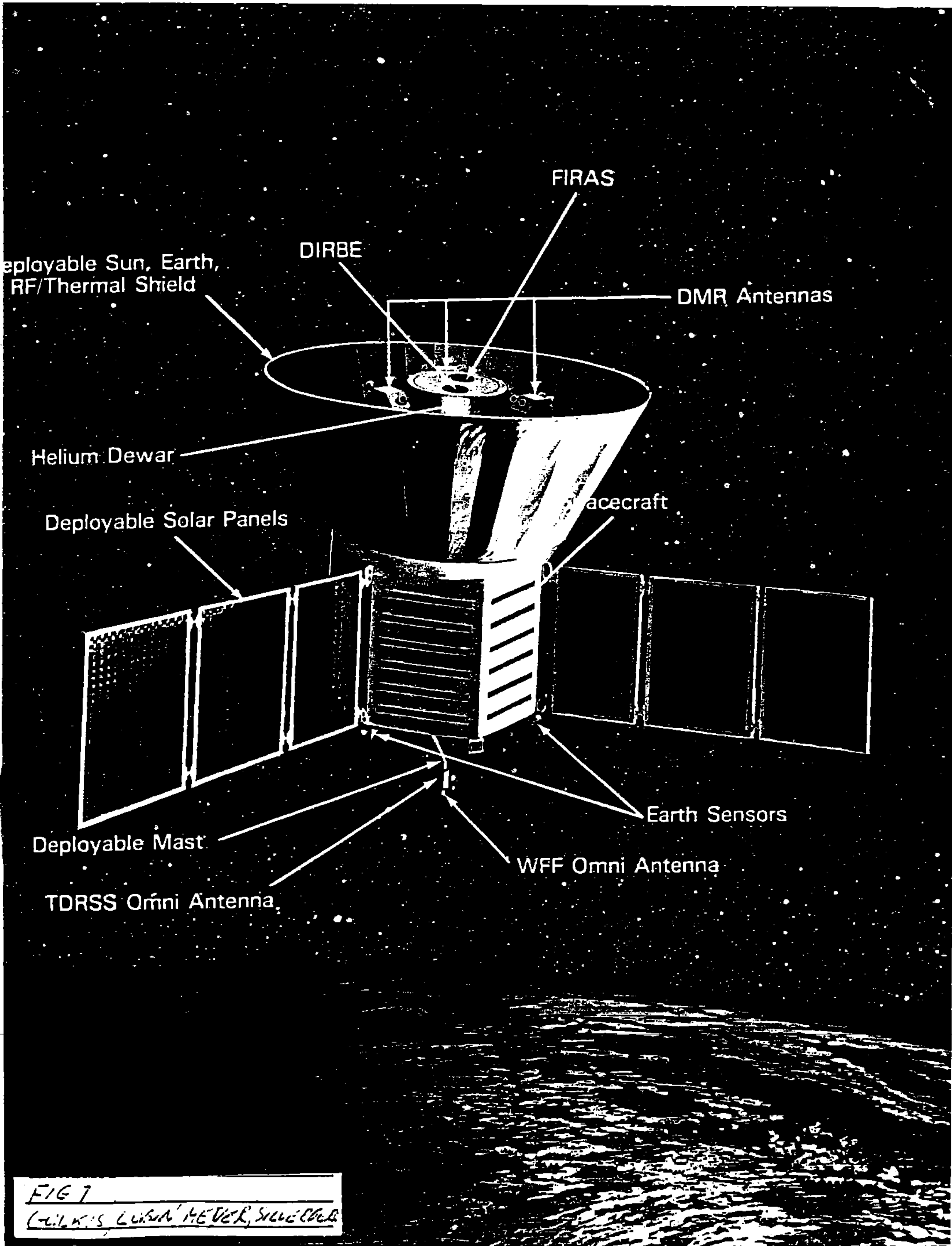

FIRAS
DIRBE
eployable Sun, Earth,
RF/Thermal Shield
DMR Antennas
Helium Dewar
acecraft
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna

FIG 7
[illegible]

Fig 6

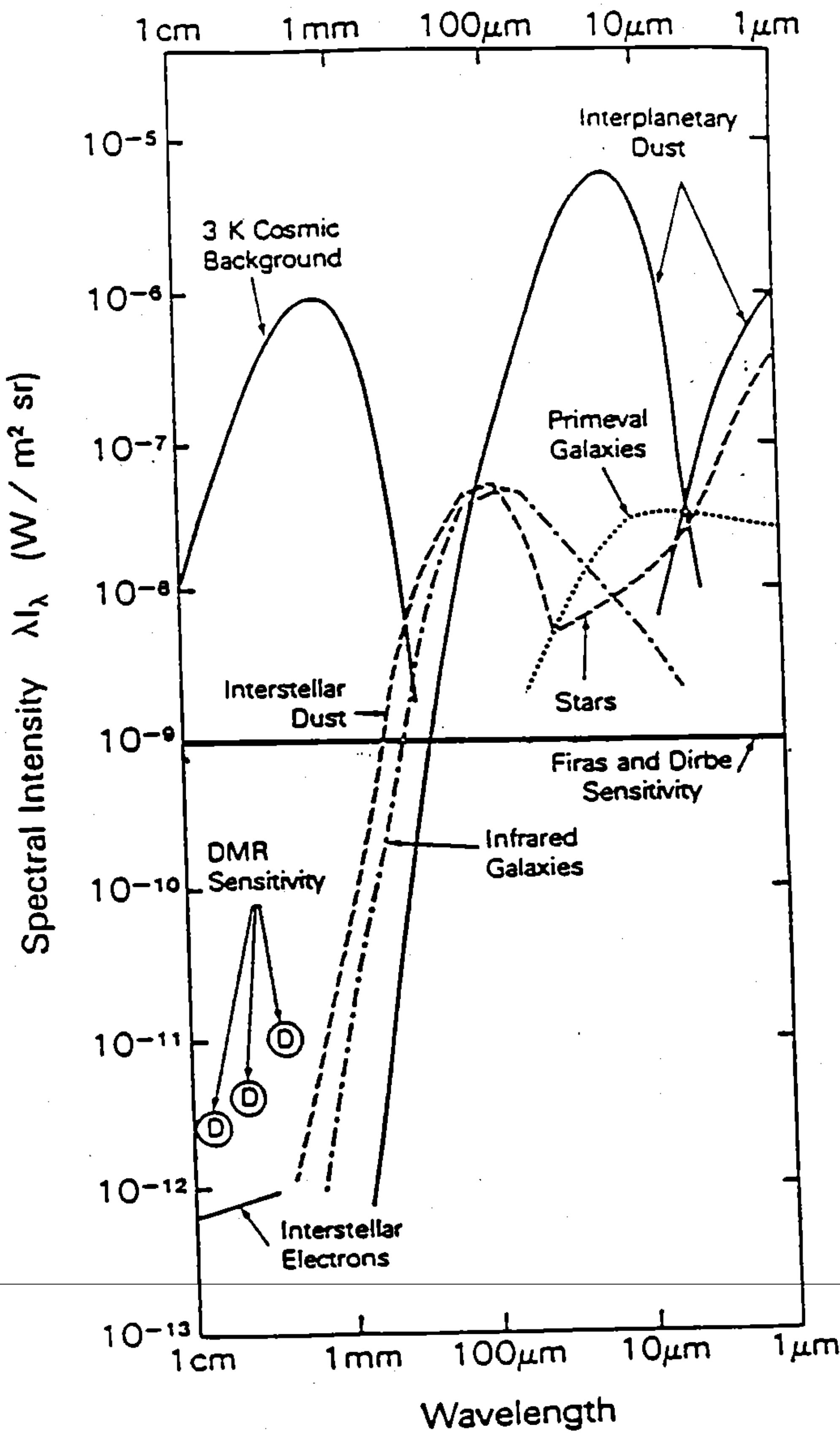


Fig 6

GULKIS, LUBIN, MEYER, SILVERBE

(PREPARED BY)	(DATE)	(REPORT NO.)
(CHECKED BY)	(DATE)	(PROJECT)

TITLE

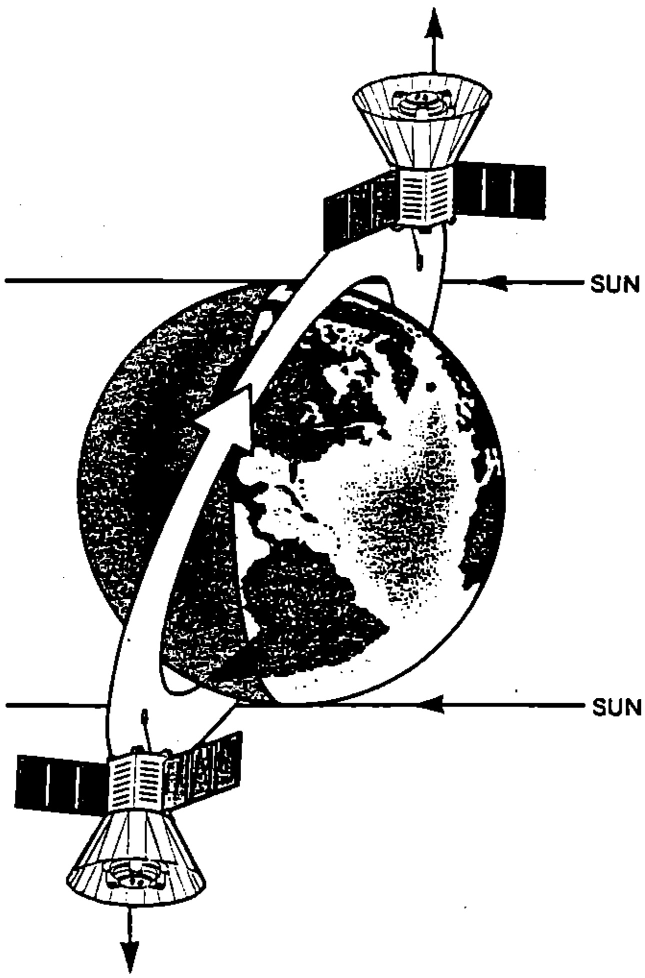


Fig 8

GULKIS, LUBIN, MEYER, SILVERBERG

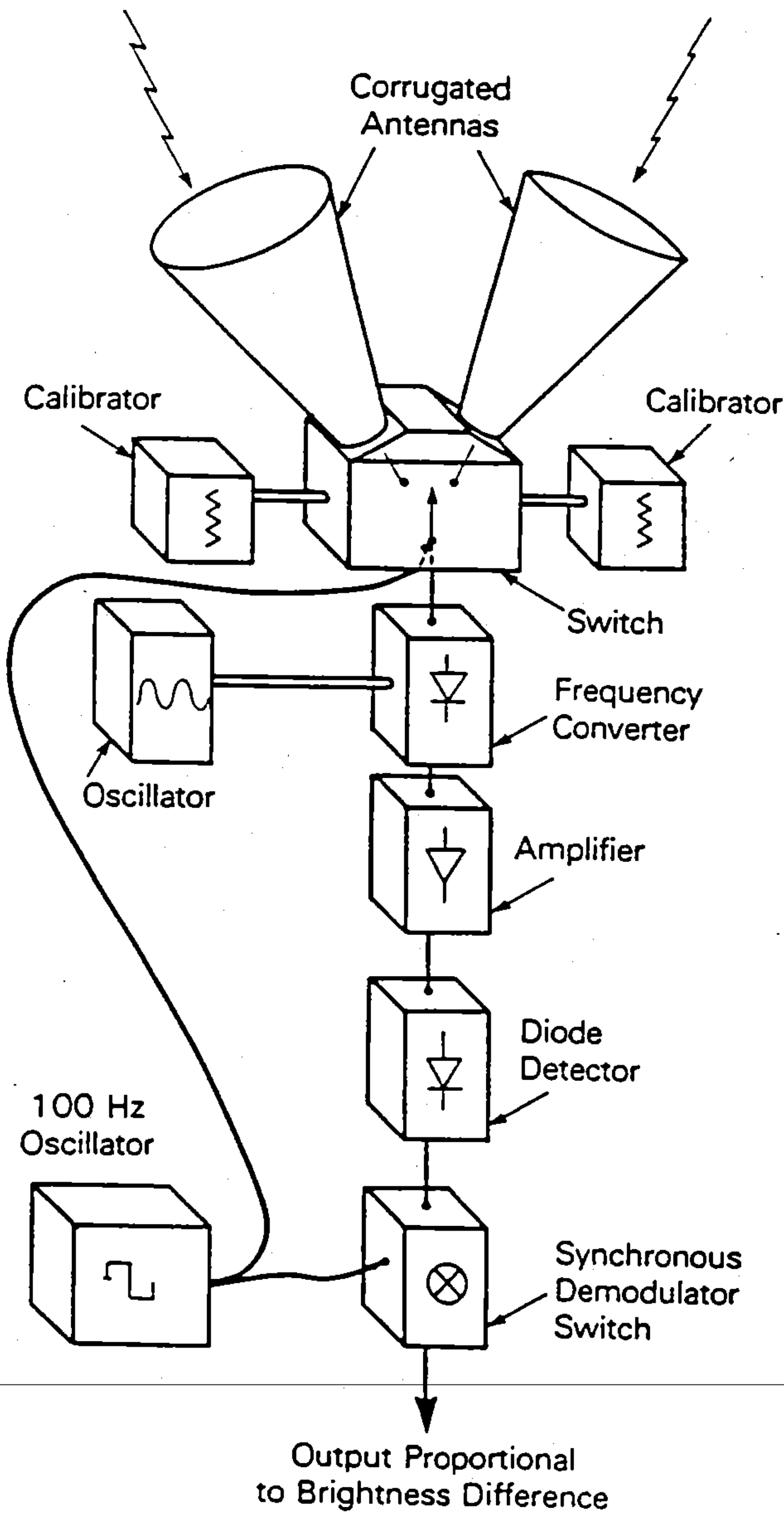


Fig 9

MEYER, SILVER.

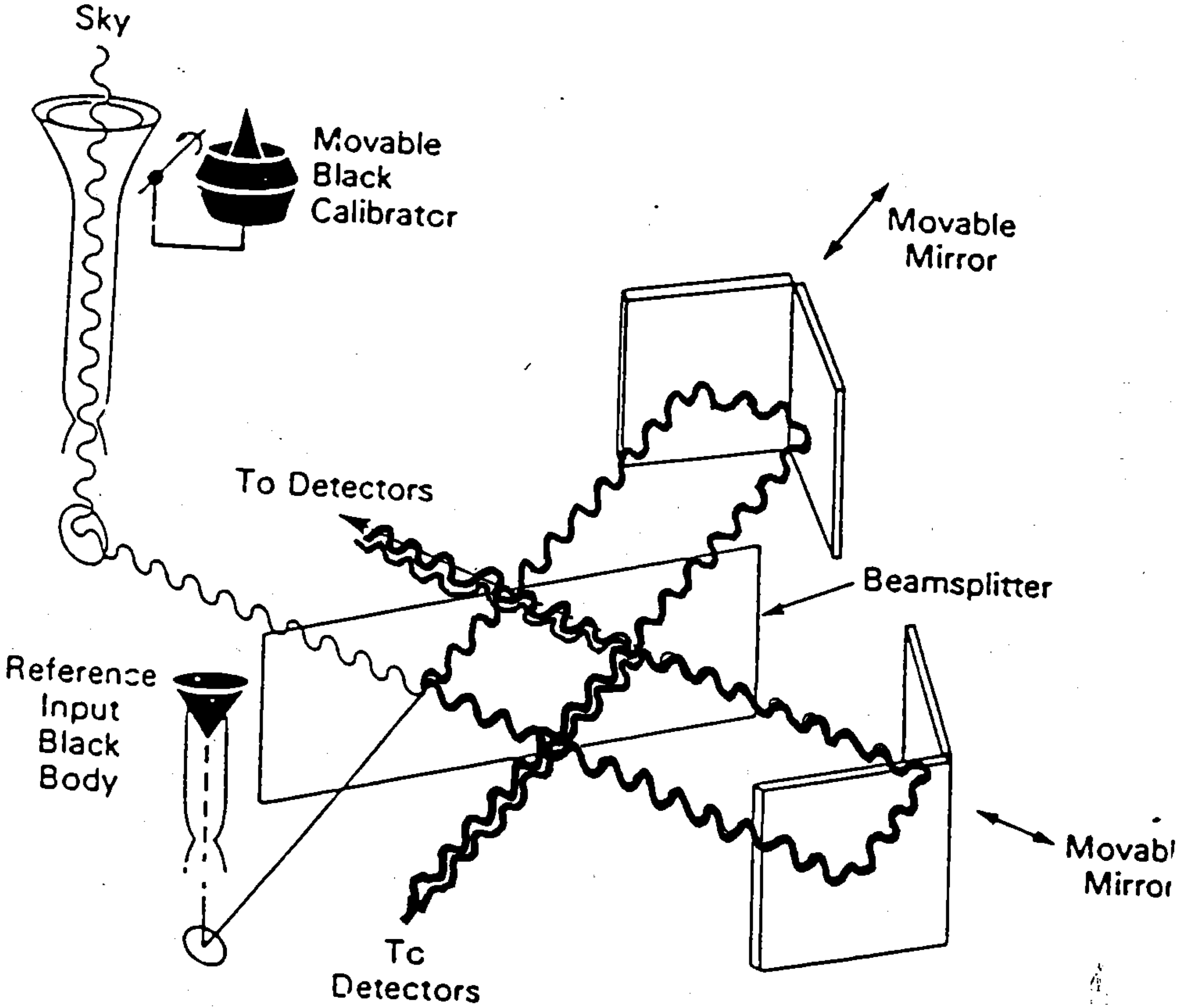


Fig 10

GuLK is Lubin, MEYER, SILK

Fig. 11

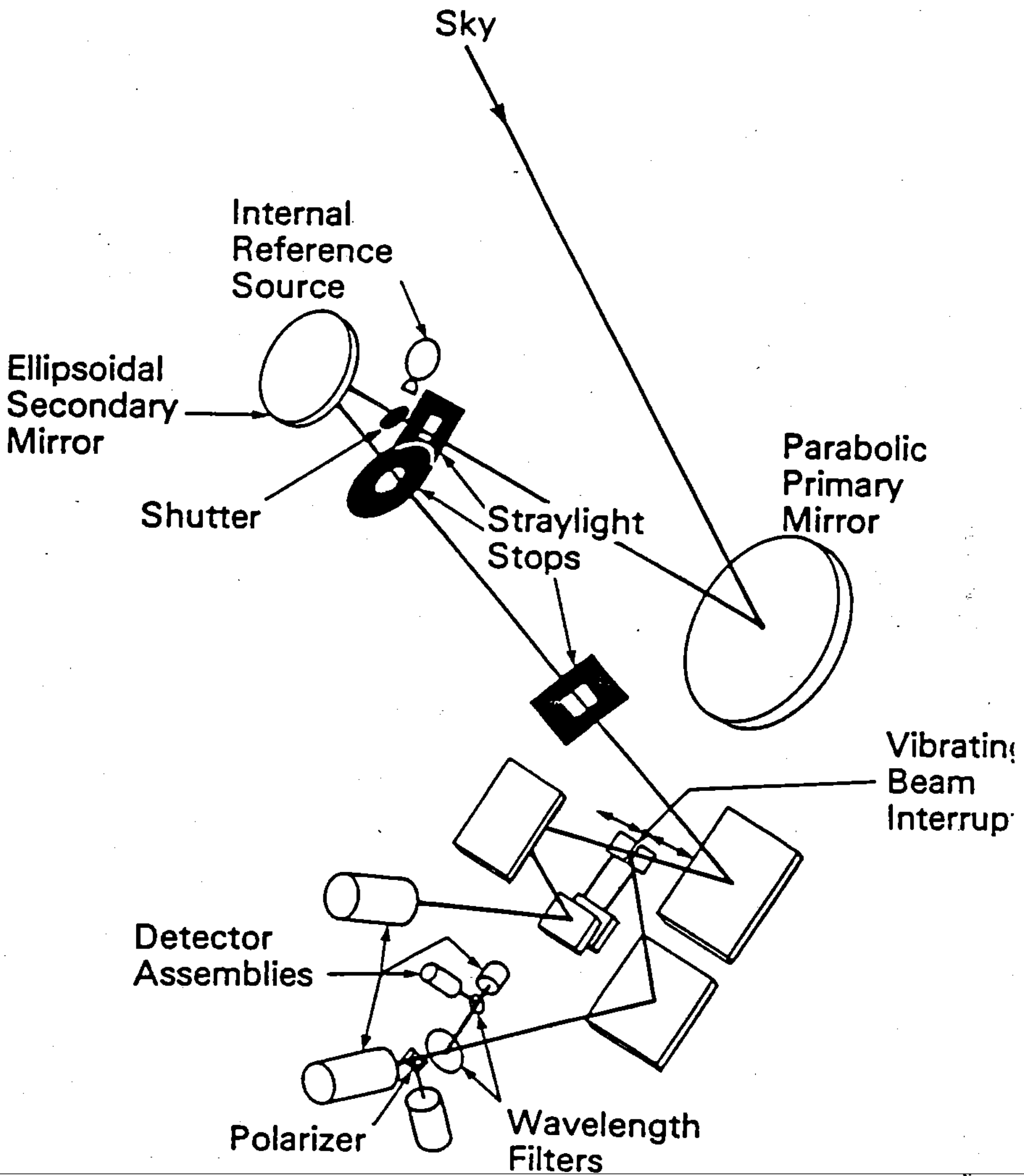

Sky
Internal
Reference
Source
Ellipsoidal
Secondary
Mirror
Shutter
Straylight
Stops
Parabolic
Primary
Mirror
Vibratin
Beam
Interrup
Detector
Assemblies
Polarizer
Wavelength
Filters

Fig. 11