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Controls Astrophysics and Structures Experiment in Space (CASES) Advanced Studies and Planning

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FINAL REPORT

by

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SUMMARY

The Science Working Group (SWG) for NASA's Controls, Astrophysics, and Structures Experiment in Space (CASES) held its first formal meeting October 25-26, 1989, at Marshall Space Flight Center. A total of 27 persons attended. The meeting was chaired by John Davis, chief of the Solar Science Branch at MSFC, and Hugh Hudson of the University of California at San Diego. In addition, several NASA and contractor representatives attended selected portions of the meeting, and the Active Controls Experiment System Laboratory was visited by members of the SWG.

Dr. Davis told the SWG that the NASA Office of Aeronautics and Space Technology (OAST), the principal sponsor, wants to be assured that CASES will provide scientifically, exciting and meaningful top-priority science. Thus, the objectives of the SWG were:

- Confirm the relevance of the science objectives

- Approve the strawman instrument design developed by a "rump" SWG session in August. and

- Review the technical design.

Cases started in December 1987 when MSFC developed a concept for a controlled structures interaction (CSI) flight experiment. It was decided that an astrophysics community, and the astrophysics observations could provide a quantitative verification of the CSI success. The selected payload will demonstrate technology for the Pinhole/Occulter Facility (P/OF), a candidate Space Station payload. OAST will provide all the flight hardware and manifest the experiment. The Office of Space Science and Applications (OSSA) will analyze the science data.

The CASES mission design was reviewed by Dr. Davis. Tutorials were given on solar and stellar observations (Hudson and Skinner, respectively), coded-aperture X-ray optics (Hurford), and CSI (Waites). Phase B studies were reviewed by Lockheed and Teledyne Brown/Ball Aerospace.

The CASES science payload design includes eight detector modules in a 3x3 array with a set of star trackers in the center. All the modules used coded aperture detectors for observations in the hard X-ray spectrum. These represent changes from the original design which had nine modules, some using Fourier transform masks. A prototype of the coded-apture module (Ramsey and Weisskopf) has flown aboard a Center for Astrophysics balloon launched to observe SN 1987a.

During general discussions Dr. Davis noted that strong interest has been expressed in aspect solutions for imaging at 1 arc-sec or better. At this point, though, it is too late in the current study to redirect the contractors to take that into account. He would be interested in redesigning the mask if the contractor can deliver sub-arc-second accuracy, but they should not redesign the system to accommodate that. Dr. Davis emphasized that the science design and objectives should not be expanded to the point that they cause more expensive refinements of the system.

Hudson said the SWG is unanimous in supporting the current CASES design

and science objectives, and is ready to proceed although some of the optics design is to be finalized. The SWG is satisfied with the Phase B requirements, but can use all the information they can provide. The sun and the central galactic X-ray source (GCS) were accepted as primary observing targets.

The SWG voted to nominate Gordon Emslie of UAH to be a payload specialist should that option be offered by NASA. Emslie argued that having a solar physicist on the mission would be crucial to the success of the solar observations.

Davis said that another SWG could be called in March at the end of Phase B. The SWG will exist until T-1 year. Then it will disband and there will be an AO for the guest investigators. Hudson added that, although individual participation is not guaranteed, "We are eager to contribute to a worthy cause; it's a good experiment." Although GCX is the only celestial target, Hudson expressed interest in the possibility of observing the Crab Nebula and terrestrial auroras. A launch date outside of the November-December timeframe (when GCX is behind the sun) is preferred.

Open items include:

- A scheme to protect the detectors from high-intensity radiation flux is needed. Suggestions include venetian blinds or a window shade. Swordy offered an unusual charge isolation concept that would eliminate the need for mechanical shutters, but which does require some electronics changes.

- There is a need to know which Shuttle orbiter will be used since that will affect the systems and mission designs (i.e., gravity gradient, moments of inertia, aerodynamic torques, etc.), and whether CASES will be a primary or secondary payload.

- Although the coded aperture concept is the baseline, Wood asked the SWG to consider changing one or two of the 64 arc-second detectors to Fourier transform to take advantage of the superior resolution they can offer.

I. INTRODUCTION

The CASES (Controls, Astrophysics, and Structures Experiment in Space) program consists of a flight demonstration of CSI (Controls-Structures Interactions) technology on the Space Shuttle. The basic structure consists of a 32-m deployable boom with actuators and sensors distributed along its length. Upon deployment from the Orbiter bay, the CASES structure will be characterized dynamically and its deformations controlled by a series of experimental control laws, and cold gas thrusters at its tip will be used to orient the Orbiter to a fixed celestial reference.

The scientific observations will consist of hard X-ray imaging, at high resolution, of the Sun and the Galactic center. The hard X-ray observations require stable (few arc min) pointing at these targets for one or more position-sensitive proportional counters in the Orbiter bay, which view the object to be imaged through an aperture-encoding mask at the boom tip.

This report gives the concensus developed at the second CASES Science Working Group meeting, which took place at NASA Marshall Space Flight Center May 16-17, 1990. An earlier "white paper" (UCSD--SP--89--17) and scientific summaries are available and form the basis for the present discussion. Some of the comments here may not make too much sense without reference to this and to other documents describing the overall program.

II. REQUIREMENTS

The CASES experiment is basically an engineering experiment in direct support of the development of large scientific instruments in the "zero-g" environment of space. The prototype instrument in this category is the Pinhole/Occulter Facility (P/OF), a mission approved for study as an attached payload for Space Station Freedom. The technology development underlying the CASES demonstration is generically known as CSI (Controls Structures Interactions). The Science Working Group strongly supports CASES, even in the case in which no scientific observations are planned; a prompt demonstration of the technology will have abundant rewards in improvements of future instrumentation in space.

The scientific observations envisioned for CASES consist of hard X-ray imaging, the most tolerant of the P/OF "focal plane" instruments of structural deformations. Indeed, hard X-ray imaging is so tolerant that its requirements on CASES may seem rather trivial. Accordingly, we list in Table 1 four levels of "requirements": CASES engineering, CASES science requirements, CASES science goals, and P/OF requirements. The first category represents the requirements imposed on the CASES experiment in the absence of any science payload, as deemed appropriate for a pure technology demonstration mission in support of this type of science mission.

Table 1. CASES Requirements

Parameter	CSI Req'ts	Science Req'ts	Science Goals	P/OF Req'ts
Counters Tip Mass	0	1	8	TBD
Pointing	3 arc min	3 arc min	1 arc min	3 arc sec
Stability	4 arc sec/s	4 arc sec/s	0.2/100 msec	0.02/10 ms
Knowledge	celestial star tracker	celestial star tracer	0.5 arc s	0.05 arc s
Observing time	0	24 hours	48 hours	permanent

Notes: (1) Pointing requirements are rms
(2) Observing time is elapsed time, including data gaps

III. REVISION OF CASES X-RAY OPTICS

The new concept for CASES envisions only a single large-area proportional counter of the MSFC design, rather than eight. The earlier concept consisted of eight pairs of counters, each pair being optimized for a given angular scale. The three coarser pairs (6.4, 19.2, 64 arc sec FWHM) were simple coded apertures, while the finest pair (1.8 arc sec FWHM) was to use a bigrid approach.

We have replaced these optics with two individual single-grid aperture modulators, at 19.2 and 3.9 arc sec (FWHM) respectively. These angular resolutions correspond to aperture sized of 3 mm and 0.5 mm, respectively; the angular resultion of the finer element is somewhat degraded by the need for convolution against the detector position uncertainty, which was fully resolved in the earlier configuration. The observations will time-share the use of these two grids in the single counter. This time-sharing could be implemented by a mechanism at the boom tip; this approach would be scientifically preferable because of the desire to pre-collimate as a means of reducing the diffuse background radiation. It would also be desirable from the engineering point of view as a means of altering system parameters for CSI studies.

IV. REDUCTION IN SCOPE OF THE CASES SCIENTIFIC RETURN

In most branches of X-ray astronomy, the scientific return scales directly with the amount of data collected, (i.e. as the area-time product), and observing time is a limited commodity on a Shuttle sortie mission. In the new layout described above, will we obtain sufficiently significant results on the primary targets?

The answer to this question appears to be a solid enough "yes" to justify the inclusion of X-ray observations within CASES. In addition to the science return, of course, these observations round out the CASES demonstration in an "end-to-end" manner. Furthermore, the time-tagged X-ray photons essentially have infinite bandwidth as fine error sensors, at least in a statistical sense, and themselves contribute to the engineering characterization of the structural dynamics. The unique and significant observational material obtainable from the reduced CASES experiment include the following:

- Position measurement of the Galactic Center hard X-ray source to approximately 0.4 arc s from 10-20 keV data; observation at higher energy is probable but will be of lower quality because of limited exposure time.

- Observation of solar hard X-ray "microflares" and identification of their location (whether active region, flaring bright point, or other).

These results will be obtained before any competitive mission can rival them, and each is a first-rank observational problem. Other results can be expected, but these two items form the basis of our decision to recommend proceeding with a limited CASES science experiment.

V. INTERFACES OF THE CASES X-RAY INSTRUMENT

The X-ray instrumentation for the CASES experiment is not only tolerant of the structural deformations (because of its time-tagged photon accumulation) but also has minimal interface complexities with respect to the overall experiment. We list these interface requirements here:

* A separate high-rate serial data

* A separate Serial command uplink

* Raw power

* Power control (on/off)

* Access to the Shuttle cooling loop

* Mechanical interface to the CASES mounting platform

* GNC data merged on-board if possible

Appendix I

CASES X-Ray Observations

August 16, 1989

White Paper

on the

CASES X-Ray Observations

by

J.M. Davis, H.S. Hudson, G. Hurford and G. Skinner

1. Introduction

The CASES experiment includes hard X-ray imaging observations of solar and non-solar sources, specifically of the possible black hole at the center of the Milky Way Galaxy. These imaging observations will take advantage of the active control of the deployable boom, for the pointing and stabilization of what will be the largest telescope yet deployed in space. The operating principle of the hard X-ray imaging observations is essentially that of a pinhole camera, in which an array of apertures at the front tip of the boom casts shadows on position-sensitive proportional counters at the rear. The shadow images thus produced can be deconvolved by correlation analysis to produce very high angular resolution, thanks to the large scale of the boom.

This "white paper" presents a description of the latest information available on the CASES astrophysics experiments. The present concept[1] differs somewhat from that represented in the earlier descriptions, including the RFP for the Phase B studies. The new concept is to go with all coded apertures in an array of eight detectors. Briefly, there are now four pairs of imagers with staggered angular resolutions in approximately the sequence 2, 6, 20, and 60 arc sec. There are no Fourier transform elements at all, so that alignment will be far easier than for earlier versions. Aspect sensing will be via a set of CCD-based star trackers mounted in a cluster at the center of the detector array. Two or three units will look at stars some 30 degrees off the pointing direction, and one will look at the back of the mask

[1] The new concept was defined in a working session held at MSFC May 23-24, 1989

to sense fiducial lights. The same system can be used for both solar and non-solar viewing.

The new concept gives great flexibility and sensitivity with a minimum of alignment difficulty. For solar observations, we get high resolution on faint sources, especially including extended sources, with excellent image quality. For non-solar observations, we get source location at the accuracy allowed by the star trackers, with sensitivity and spectral resolution exceeding anything planned now for hard X-ray observation.

2. Optics

2.1. X-ray Optics

It was decided at the May meeting to revise the strawman concept for the X-ray optics so as to eliminate the Fourier-transform grids. The motivation was that the spatial resolution of the proportional counters (better than 1 mm FWHM up to 60 keV) implies that coded aperture imaging could be extended to down to 6.4 arcseconds directly, which is much better than previously baselined. The remaining step to achieve resolution approaching 1 arcsecond could then be done using a fine coded aperture mask at the top, and a regular array of fine holes at the bottom. This still requires a second grid, as the Fourier transform elements did, but now the requirement for precise alignment has been effectively removed. The holes in the bottom grid serve merely to sharpen up the spatial resolution of the detector by ensuring that there is only one pixel per spatial resolution element. The penalty in sensitivity for doing this is only about a factor of three compared to using 2-dimensional Fourier grids. This is a good price to pay for the improved image quality afforded by the coded aperture, compared to that of the sparsely populated (u,v)-plane that a few subcollimators could provide in a straight Fourier transform imager.

The present strawman optics design (which certainly willl need fine tuning) is as follows:

- There will be eight detector modules, with 27 $\times$ 27 cm active area each, based upon the MSFC electrical design.
- The detector modules may be grouped in 4 pairs, with each pair viewing a coded mask (tungsten or equivalent) of 0.5 mm thickness.
- The detector pairs are mounted around the edge of the array with the aspect system in its center.

- A precollimator at the detectors will be used to suppress the diffuse background X-rays and isolate different mask elements.

The aperture size (center-to-center) and corresponding resolution for each of the four mask types are as follows:

Aperture	Resolution
10 mm	64 arc sec
3	19.2
1	6.4
0.25	1.8*

* It is the convolution of the 250-micron (top grid) and 300-micron (bottom grid) apertures that yields the 1.8 arcsec resolution.

The hierarchy of resolutions is needed for solar observations where extended sources are expected, because of the distinct variation of SNR with angular scale in a typical coded-aperture image. Note that the uniform response of the URA-type coded aperture has been sacrificed to some extent, because of the possibility of some illumination from beyond the mask boundary, but it was felt that this would be acceptable given the large number of apertures. The finest mask would have 250-micron apertures on 300-micron centers to make it self-supporting. The detectors viewing this mask would have a second (bottom) mask with 300-micron apertures on 1 mm centers.

The throughput at the finest resolution is 3.1% (compared to 50% for the others). The total effective area is 45 cm^2 at the finest resolution and 2232 cm^2 total. The primary advantage of the new configuration is the superb morphological capability, particularly for solar viewing. Secondary advantages include a greater immunity to relative twist (displacements of top grid relative to the detector via rotation around the Orbiter z axis) and simplifications inherent in using one rather than two different imaging techniques.

2.2. Aspect System

The new concept envisions an array of two-dimensional star trackers at the center of the proportional-counter array. One of these star trackers (or equivalent devices) would view a set of fiducial lights on the occulter, and the others (two or three, depending upon the tradeoffs) would view star fields at angles of some 30 degrees to the line of sight. At this large an angle, a star tracker could be baffled well enough to work even during solar pointing, so that the same instruments could be used for both solar and non–solar pointing. The choice between two and three trackers depends upon the precision required for relative yaw displacement (see below) and the probability of solar or terrestrial blockage of one of star trackers during a given observation.

In this concept (Fig. 1), the star trackers would be mounted in one compact unit at the center of the detector array. Stellar and fiducial measurements would be made on the update period of the trackers, assumed here to be 100 msec or better. Such an arrangement would place no difficult requirements on the coalignment of the detectors and trackers, beyond the metrology needed to determine their relative positions to a fraction (nominally 10% rms) of the position resolution of the counters.

The area available at the center of the array may or may not be adequate for installation of the star trackers; if not alternative positions at the edge of the array would also be possible.

3. Pointing Requirements

3.1. Note on Coordinates

It will spare us from a lot of confusion in the future if we adopt Orbiter coordinates for CASES. To review briefly, the (x,y,z) coordinate system of the Orbiter is the following: x towards the nose, y to starboard, and z downwards. The corresponding rotations about these axes are called roll, pitch, and yaw.

3.2. Pointing Requirements

A telescope of the CASES type differs mechanically from a classical instrument in that there isn't simply a rigid tube that has to be pointed in the right direction. Instead, the different components of the telescope have independent requirements. In a sense, the servo control functions are analogous to those of image motion compensation in a classical telescope, but the fact that the X–ray imaging is done with "shadow optics" rather than lenses or mirrors makes this analogy a weak one. In this section we review the basic ideas that govern the requirements on pointing accuracy and stability.

The pointing direction for a single CASES element (detector and corresponding mask area) is defined by a line connecting fiducial points on the mask and on the detector, *e.g.* the center of the detector and the center of its corresponding mask. Ideally, the pointing directions for all eight elements coincide, and we call this vector p. The area of the mask defines the field of view of the image, and the source to be observed must be kept well within this field of view. Thus if the vector s describes the direction to an astronomical target, $\angle(\mathbf{p}, \mathbf{s})$ must be less than a given limit. We set this at 2 arc min (rms) for the present CASES configuration.

The X-ray counters must have a mechanical precollimator to exclude diffuse background X-ray flux. If we represent this precollimator by the vector d, then $\angle(\mathbf{d}, \mathbf{p}) < 2$ arc min for the current choice of a 1° (FWHM) collimator. Note that this is the same numerical precision as for the $\angle(\mathbf{p}, \mathbf{s})$ limit, but for a different physical reason.

One more physical constraint on the angle $\angle(\mathbf{p}, \mathbf{s})$ has to do with "grid collimation." The mask material is thicker than the width of the finest holes, and this also restricts the field of view. For CASES this effect probably does not come into play for reasonable boom deflection angles.

3.3. Pointing Stability

Because the CASES X-ray detectors record individual photon arrivals in three coordinates (x, y, and t), there is no requirement on stability in the classical sense — that is, assuming that the aspect solution is known exactly. This assumption is not right, of course, and for the present baseline configuration, star trackers update the aspect information only every 100 msec. Therefore, pointing jitter on this or shorter time scales, in excess of about 1 arc s peak-to-peak, would ruin the observations. We can translate this into actual stability rates by taking as a limit 10% of the FWHM resolution per 100 msec. For 1.8 arc s, this therefore amounts to 1.8 arc s per second, integrated over all higher frequencies present in the dynamics.

The yaw stability rate can be deduced from this limit as follows: if the mask and the detector yaw relative to one another at an angular rate greater than 1/10 pixel at the edge of the field of view per star tracker update time, the image will be blurred.

4. Operations

An "Extended Duration Operations" or EDO capability would be highly advantageous for the CASES X-ray observations. With additional equipment (for example additional fuel cells) an Orbiter can stay in space for about two weeks. Obviously, this would much more than double the CASES science return, modulo other factors in Shuttle operations such as crew time, so the EDO option would be preferable. The price paid by the Orbiter is a smaller payload, but CASES is not particularly heavy and so this factor may not be too significant.

The additional time would be used for solar viewing and for additional non–solar targets. The latter could include the following:

- The Crab Nebula (supernova remnant)
- Cen A (radio galaxy)
- M31 (ordinary galaxy)
- The Perseus cluster of galaxies
- SS 433 (oddball galactic X–ray source)
- Jupiter

5. Solar Filter

The X–ray counters probably cannot exceed 10,000 counts s^{-1} (per counter) and still provide quantitative data. This imposes a severe restraint on solar observations if much soft X–ray flux is to be admitted to the counters. One solution to this would be the equivalent of a "neutral density filter" for X–rays, to cut down this overpowering soft X–ray flux in a manner permitting subsequent calibration of the observations. In practice a true neutral–density filter is impossible, so the actual filter must simply attenuate the soft end of the spectrum. The solar filter must be removable, so that non–solar (and solar, in the case of low activity) observations can be carried out as sensitively as possible. The operation of the solar filter must be automated, so that a bright flare will trigger it "on" and maintain high–quality observations.

Appendix II

Non-Solar Scientific Objectives for CASES

Non-solar Science Objectives for CASES

Overview

1) The Galactic Centre

- Where is the nucleus of the galaxy?
- What is the nature of the x-ray emission from the nucleus ?
  - collection of point sources ?
  - diffuse emission ?
  - point source (*eg* black hole) ?
  - does it coincide with Sgr A* or lie in IRS16 ?

2) Other targets

- The Crab Nebula
  - How and where are the electrons accelerated?
- Pin-pointing GRO Sources
  - Overlap in energy range
  - 1″ positions provide unique stellar identification
- Nearby galaxies
  - M31: study complex of sources in bulge at hard x-rays
  - M33, M81 (and M31?) nuclear emission - hard x-rays from nuclei of normal galaxies ?

(1) The Galactic Centre

Summary

Active galactic nucleii (AGNs) in the form of quasars. radio galaxies, BL Lac objects and Seyfert galaxies are increasingly thought to be manifestations of similar type of phenomena in the nucleii of the galaxies. These objects constitute only a few percent of all known galaxies but there is evidence that many – perhaps all – galaxies are to some extent 'active' in this sense. At least for the more pathological forms of this nuclear activity, such as that in quasars, an accreting massive black hole is usually assumed to be involved.

The centre of our galaxy shows various signs of violent processes and is 70 times closer to us than any other galactic nucleus (and 2000 times closer than the nearest Seyfert nucleus); thus it is much more readily studied. This leads to questions such as:

- Are the violent processes at the centre of our galaxy related to the activity in AGNs ?
- Where, exactly, is the nucleus of our galaxy ?
- Is there a massive black hole there ?

Visible light from the GC is attenuated by a factor of 10^{12} so observations are limited to the radio, infra-red and x-/gamma-ray bands. The nucleii of AGNs are frequently very luminous in all three of these bands and so all are very relevant to the above questions. Extensive work has been done in the radio and infra-red bands, giving inconsistent answers to the first two questions and no clear cut conclusion about the third. Observations with high energy photons may help in resolving these problems but we are only just starting to achieve the necessary sensitivity and angular resolution.

The Radio Picture

The Sgr A complex which contains the galactic centre is the brightest radio source in the galaxy and embedded within it lies a unique ultracompact non-thermal radio source, Sgr A*. Various lines of evidence suggest that Sgr A* may be an accreting massive black hole and the central 'engine' in the nucleus of the galaxy:

- It is central – Sgr A* lies within Sgr A (West) and at the core of a complex of loops and arches (see Fig. 1 and *eg* Yusef-Zadeh and Morris, 1987), but in particular it is at the centre of a 'mini-spiral' structure about 10 light years in extent (Fig. 2; also see review by Lo, 1986).

- It is extremely compact – VLBI techniques show it to be less than 20 AU in extent, with an implied brightness temperature in excess of 7×10^8 K (Lo *et al.*, 1985).

- It is almost certainly massive – its proper motion has been shown to be less than 40 km/s (at 10 kpc) (Backer and Sramek, 1987). If it was of mass comparable to that of the stars in the region it would be expected to have a similar velocity to theirs. A velocity dispersion of 72 km/s has been found for 21 stars for which radial velocities are available (Rieke, Rieke and Paul, 1989).

- It is powerful – the radio luminosity of the compact component is $\gtrsim 10^4$–10^5 times that of pulsars or of the radio sources associated with some x-ray binaries, the only other comparably compact sources known in the galaxy.

The infra-red picture

Infra-red observations reveal:

- A star density rising rapidly towards the kinematic centre of the galaxy, in a way which is consistent with the density cusp expected around a point mass dominating the central region (*e.g.* Allen and Sanders, 1986). It is, however, also consistent with an isothermal distribution with a small core radius.

- Thermal emission from dust grains in a ring surrounding a central cavity which is comparatively free of dust and gas and which must contain a central source or sources providing the optical/uv flux which heats the dust (Becklin, Gatley and Werner, 1982).

- Infra-red line emission (HI Brα, HeI and NeII) revealing both systematic (rotational and streamer) velocities and turbulent motion leading to a 'broad line region' analogous to that seen in Seyfert galaxies (see review by Genzel, 1988). Analysis of the velocities has been taken by some to demonstrate the existence of a central mass concentration consistent with a massive black hole.

- A complex of near IR sources (IRS16) which lies close to the centre of rotation and at the centre of the 'broad line region' and which forms the peak of the density cusp (Fig. 3)

Agreement and discrepancies between IR and Radio

Both infrared observations of heated dust and radio/IR observations of ionized gas imply a considerable flux of ionizing radiation, presumably largely UV, forming an evacuated cavity or 'bubble' in the central 2 pc (6 light years) radius. A few times 10^{50} L_α photons per second, corresponding to a luminosity of $\sim 5 \times 10^{39}$ erg s^{-1}, are needed from a source whose temperature (from the presence of NeII) must be $\lesssim$ 35000 K (Lacy *et al.*, 1982).

Rotation and kinematic studies in both the IR and radio are consistent with, but do not necessarily require, a mass of 10^6 solar masses within 0.1 pc (2 arcsec) of the nucleus (Fig. 4).

There is a major difference between the radio and infra-red measurements: the former point to a unique central object (Sgr A*), whereas the latter show a cluster of at least 10 objects of comparable near-IR luminosity. This difference leads to two extreme views in which the ionizing flux and other manifestations of central 'activity' are powered either by a single central 'engine' (*eg* Gatley, 1987) or by a group of late O stars resulting from a recent (but not too recent) burst of star formation (*eg* Allen, 1987).

Furthermore, when a precise comparison is made the position of Sgr A* does not coincide with the centre of the IRS16 complex. It lies ~1 arcsec to the West. There is some evidence that Sgr A* corresponds to a relatively weak component of IRS16 (IRS16NW, Biretta *et al.*, 1982; Object A, Storey and Allen, 1983; CCD2, Henry *et al.*, 1984), but recent measurements (Rieke, Rieke and Paul, 1989) place upper limits which are barely consistent with such an alignment (Fig. 6). Certainly there is no strong IR source at the position of Sgr A* and if it is supposed that the radio source is the origin of all the ionizing radiation this is not consistent with any normal combination of spectrum and extinction.

X-rays and Gamma-rays – getting to the core of the matter

X-ray and gamma-ray measurements potentially open up a new window into what is going on in the nucleus of the galaxy - and one which is particularly appropriate for studying high energy processes such as are thought to be present. All measurements so far, particularly those with very hard x-rays and gamma-rays, have been severely limited in angular resolution, but there is already evidence that observations at these wavelengths will be productive.

It has long been known that the general region of the galactic centre is a strong source of hard x-rays and gamma-rays. Particularly interesting is the detection of 511 keV positron annihilation radiation, one component of which now definitely seems to be variable (Gehrels *et al.*, 1989) even though earlier reports of variations could perhaps have been the result of comparing results from instruments with fields of view of differing sizes (Share *et al.*, 1988). The variability indicates a point source origin and although the direction is known only to a few degrees it has been natural to suggest that the galactic nucleus and/or Sgr A* is responsible. The demonstration with the Spacelab-2 (SL2) XRT (Skinner *et al.*, 1987) and with GRIP (Cooke *et al.*, 1989) that the majority of the hard x-rays from the region come from a source (1E1740.7-2942) $\sim$ 1 deg from the nucleus and also the suggestion that the disappearance and reappearance of the 511 keV line is connected with similar variations in GX1+4 (McClintock, 1989), even further away, suggest other possibilities. Nevertheless an association between the unique gamma-ray source and the exceptional processes going on in the region of the nucleus remains likely.

The most detailed measurements have been obtained at much lower energies with the Einstein observatory, using the IPC detector (Watson *et al.*, 1981). Unfortunately the high angular resolution of the HRI detector could not be utilized because at the very low energies at which it was most sensitive the intervening clouds are still opaque. With the IPC in the focal plane the observations were possible in a narrow band above $\sim$2.5 keV where the clouds start to become transparent and below the $\sim$4.5 keV limit of the mirror. The IPC images showed a complex of compact weak sources embedded in a cloud of extended emission (Fig. 6). One of the brighter sources coincided, within the $\sim$arcmin accuracy, with both IRS16 and Sgr A*.

These observations were extended to somewhat higher energies, although with slightly poorer angular resolution (3 arcmin) and sensitivity, with the coded aperture XRT on the Spacelab 2 mission (Skinner *et al.*, 1987). 3–30 keV X-rays were detected from a source, which again was consistent with either IRS16 or Sgr A* (Fig. 7) . Either because of the uncertainties associated with estimating the effects of interstellar absorbtion at the Einstein IPC energies, or because of source variability, the flux detected was $\sim$7 times stronger than that expected on the basis of the Einstein observations. There is some indication of finite extent or structure within the hard x-ray emission (Fig. 8; Skinner *et al.*, 1989).

The only other information we have concerning x-rays from the region immediately around the nucleus are the observations of a transient $54 \pm 27''$ from Sgr A* with Ariel 5 (Eyles *et al.*, 1975) and some lunar occultation measurements with Ginga (Tanaka, private communication). The latter also revealed a transient (or highly variable) source, as well as emission extended on scales from 4 to 120 arcmin.

Null detections of emission from the galactic nucleus with the Spartan-1 scanning collimated detector (2–10 keV) and with the GRIP balloon payload at higher energies are consistent with the level of the Einstein/SL2 detections.

Thus although we know that the galactic centre does emit x-rays, there is no data comparable in precision with that at radio or IR wavelengths. In particular it is not possible to say whether the emission is extended on the scale of the IRS16 complex, or, if it is point emission, whether it comes from Sgr A* or from elsewhere in the region. Nor do we know what its spectrum is like and if the emission extends to high energies.

What CASES can do

Observations are needed with high sensitivity, very good angular resolution and with response to high energies. CASES can provide all of these.

The range of angular resolutions (64 arcsec down to 1.8 arcsec, although with limited sensitivity for the finest system) will allow the structure to be studied on all scales down from that of present observations.

Ideally one would like to be able to find the centroid of the emission (whether point-like or diffuse) to a precision of better than 1 arcsec. Finding the source position within the image to the necessary accuracy should be possible with the 6.4 arcsec resolution modules (requiring finding the position of the centroid to ~10 times better than the FWHM of the instrument, which is commonly achieved). If the emission can be detected in the 1.8 arcsec modules then this aspect of the problem becomes trivial. Positioning the image on the sky depends on the absolute accuracy of the star trackers and of the alignment determination system, which must be capable of corresponding accuracy.

Initial estimates for a source with a 3-30 keV luminosity of 6×10^{36} erg s^{-1} (as found by Skinner *et al.*, 1987) with a spectrum like that of the Crab nebula suggest that in a 15-25 keV band, in 24 h of useful observation a 36σ signal would be obtained at each of the lower resolutions and 2.2σ at 1.8 arcsec. In an 7-12 keV band the corresponding figures would be 170σ and 5.2σ.

The use of fluorescence gating means that the sensitivity is still good at high energies (30-50 keV). We estimate if it has a crab-like spectrum the nucleus will be detectable up to 50 keV.

(2) Other Sources

The Crab Nebula

The existence of a bright, time modulated point source of extremely well known position (NP0531, the Crab pulsar) will make observations of the Crab Nebula particularly valuable for calibrating the attitude and alignment measuring systems as well as for the usual energy response and efficiency verification. But the pulsar will also allow extremely accurate image motion compensation with little reliance on the attitude systems. The resulting precise images with the wide energy range and good high energy response of CASES will allow unique science investigations during these observations.

In the simplest description the Crab nebula x-ray emission is synchrotron radiation from electrons accelerated 'by the pulsar'. Higher energy x-rays come from more energetic electrons, which can travel only limited distances before losing their energy. For electrons producing x-rays of energy $E_{50} \times 50$ keV, the distance they can travel at $v = c$ corresponds to $11/E_{50}^{1/2}$ arcsec (taking $B = 6 \times 10^{-4}$ Gauss, $d = 2$ kpc).

At low x-ray energies both the size and the form of the x-ray emission have been well established using reflecting telscopes (see for example the analysis by Brinkmann *et al.*, 1985, of the *Einstein* data). At higher x-ray energies we have only occultation observations (Ricker *et al.*, 1975; Kestenbaum *et al.*, 1975; Staubert *et al.*, 1975; Ku *et al.*, 1976 ....) and Rotation- and Scanning-Modulation Collimator data (Makishima *et al.*, 1981; Pelling *et al.*, 1987), giving estimates of the size and position of the centroid of emission with repect to the pulsar.

At low energies the extent of the emitting region is ~100 arcsec (FWHM) and this shrinks with increasing energy as might be expected from the electron lifetime considerations (Fig. 9). But it is clear that simple models cannot explain the details of the behaviour. There is an offset from the pulsar of the centroid of the emission by >10 arcsec – an amount comparable with the expected maximum distance that the electrons are expected to be able travel – and considerable elongation of the emitting region. More complex models involving bulk transport (Aschenbach and Brinkmann, 1975) and particle re-acceleration (Kennel and Coronoti, 1984) have been invoked.

CASES will be able to actually map the distribution of the high energy emission in a way analogous to that done at low energies with *Einstein*. Because of the short electron travel distances, the high energy emission in many ways gives the most direct evidence about the acceleration sites and the transport mechanisms involved. It is well suited to addressing such questions as:

- Is the progressive concentration to the northwest of the pulsar with increasing energy related to the toroidal shape of the low energy emission in the way suggested by Brinkmann *et al.* (1985) ?
- Is reacceleration taking place in the vicinity of the 'wisps' ?
- Are the electrons initially transported by winds without significant radiative loss ?

Pin-pointing GRO Sources

The GRO instruments all have angular resolutions $\sim 1°$ and so will be able to position newly discovered sources to at best a few arcminutes. Experience has shown that the sources which are important at even 100 keV are not necessarily distinctive in measurements made at ~1 keV (*eg* 1E1740.7-2942. Skinner *et al.*, 1987, Cooke *et al.*, 1988). CASES will have good overlap with the bottom end of the GRO energy range and provide arcsecond positioning capability, which is almost always sufficient for a unique stellar identification. Flying in 1993, it will this be ideally placed for follow-up studies of sources found with GRO.

Other galaxies

Given observing times of 12–24 h, CASES will have sufficient sensitivity to detect the brighter individual sources in nearby galaxies.

Ninety point sources were detected in the Andromeda Nebula (M31) with *Einstein*, including 19 within 2 arcmin of the nucleus (Long and Van Speybroeck. 1983). Although only capable of detecting the brightest of these, CASES will be the only instrument before AXAF to be able to resolve and study these sources and is (except for P/OF) the only projected instrument capable of doing so at high energies.

It will also be possible to extend the work on the nucleus of our galaxy to those of nearby galaxies. Luminous nuclear sources have been observed in M33 and M81 which, if they have have hard spectra would be detectable with CASES. (A variable source which may be associated with the nucleus was also seen in M31).

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G.K.Skinner

23-Oct-89

STRUCTURE OF SGR A COMPLEX

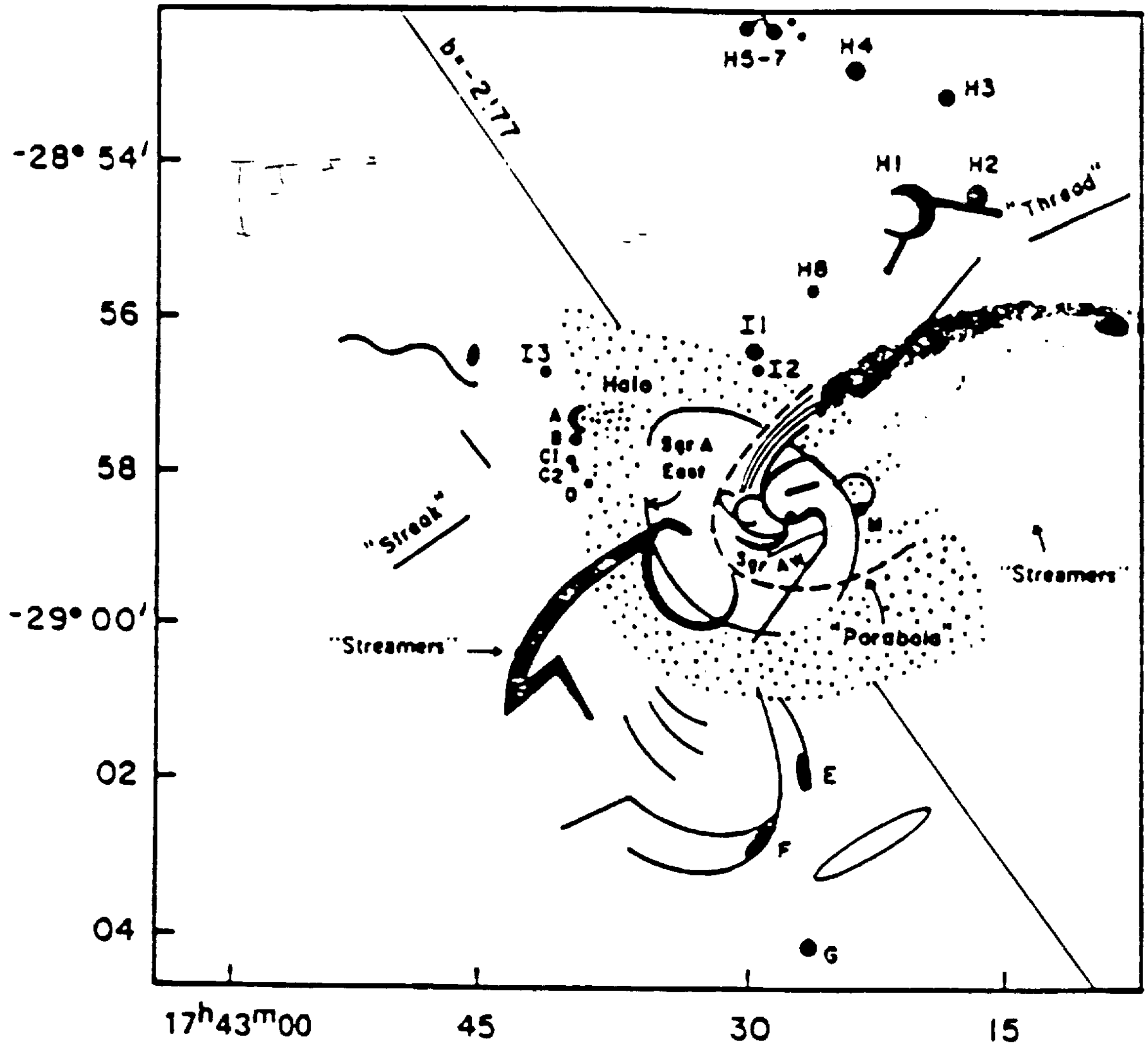


Figure 1. Schematic view of structures identified in radio images of the Sgr A complex. From Yusef-Zadeh and Morris (1987)

Code

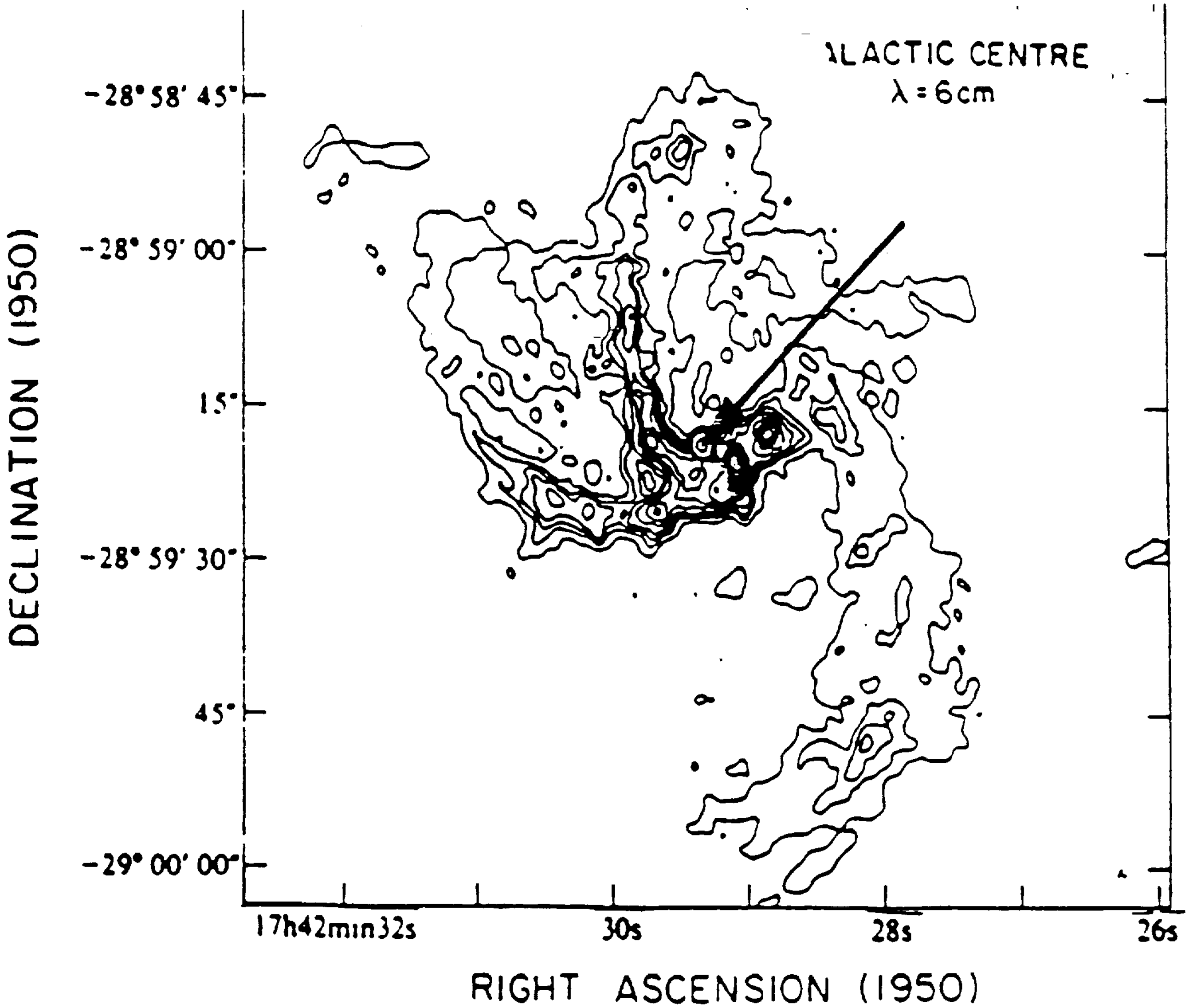


Figure 2. VLA map of Sgr A West. The compact non-thermal source at the map centre is Sgr A*. (Lo and Clausson, Nature, 306 p647, 1983).

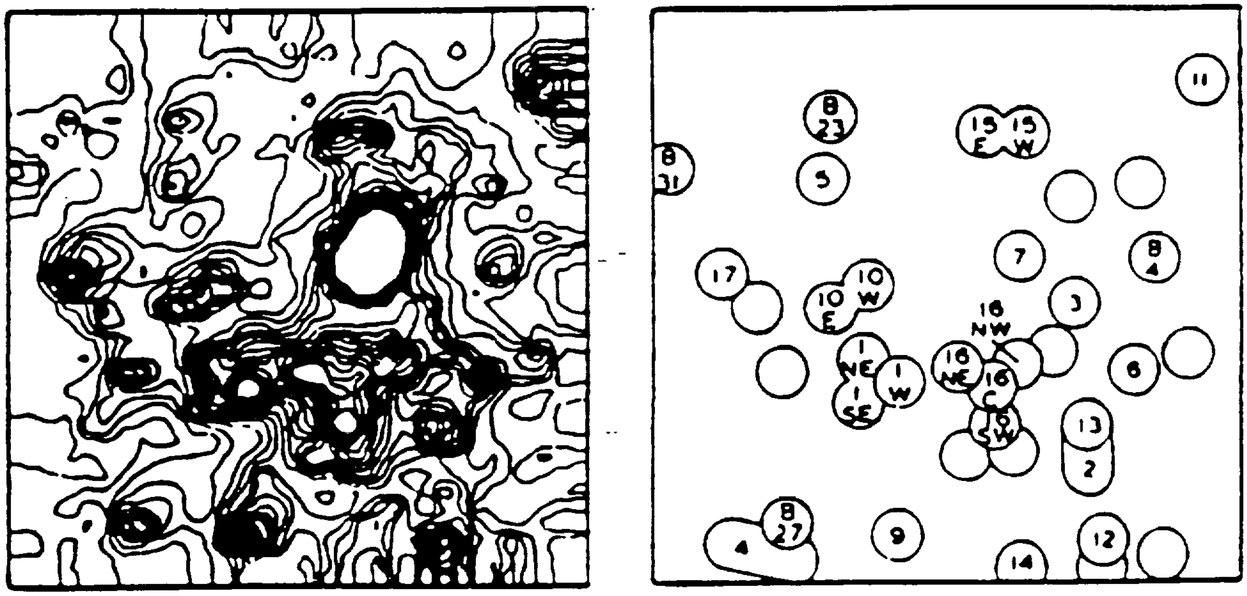


Figure 3. (a) Near Infra-red (1.6μm) image of the galactic centre obtained with a 32 by 32 detector array (0.85 arcsec pixels). The frames are 27 arcsec square. (b) source 'IRS...' names. (Rieke, Rieke and Paul. 1989).

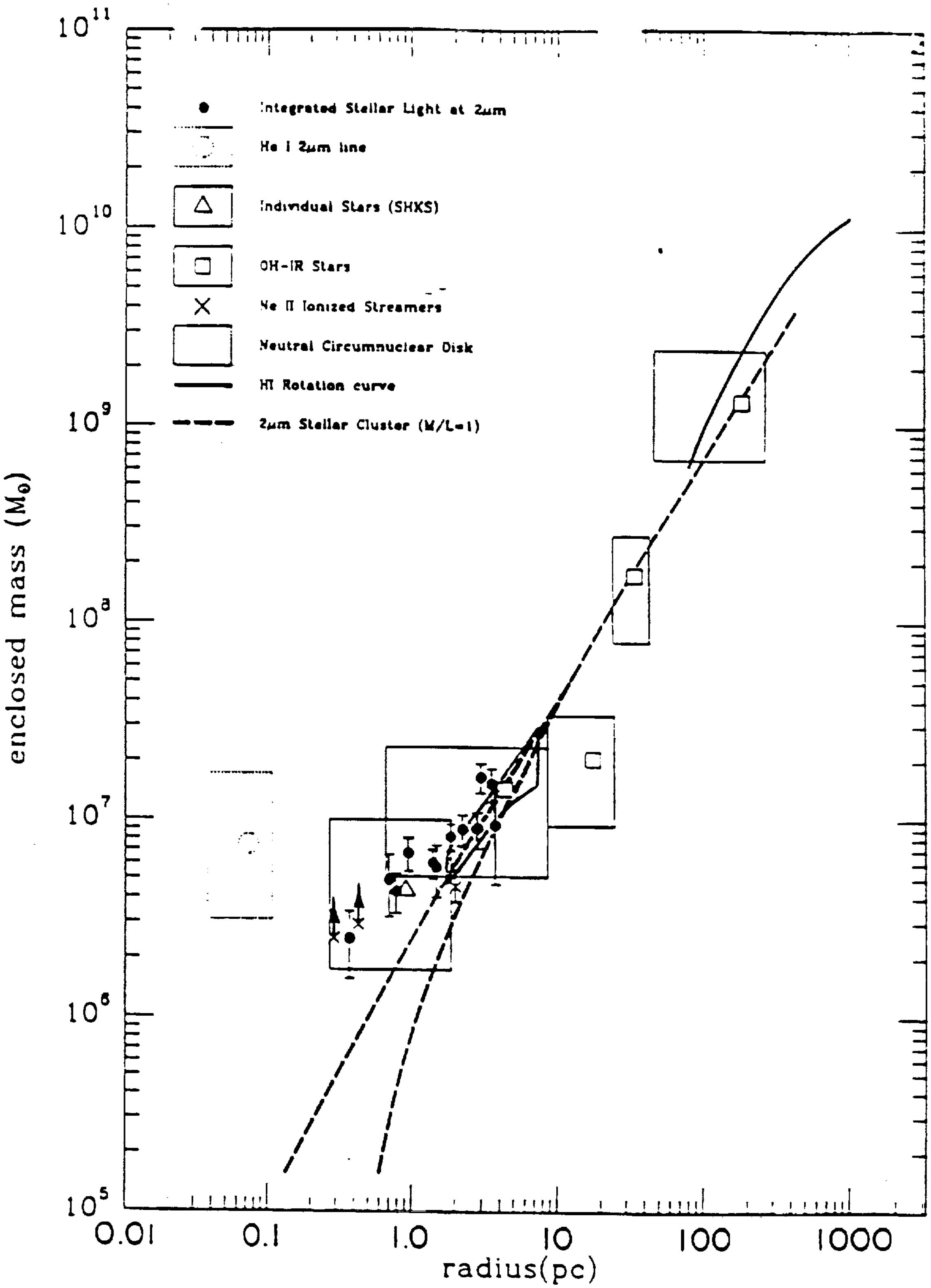


Figure 4. Estimates of the total mass within a given radius of the galactic centre. The filled circles are from kinematics of integrated starlight, while the other symbols are derived from kinematics of ionized gas, and OH/IR stars. The dashed lines are estimates of the mass in stars in the stellar cluster, derived from the 2.2μm light distribution, assuming M/L=1 and core radii of 0.1 and 1 pc. From Sellgren, 1989; Figure originally due to Genzel and Townes.

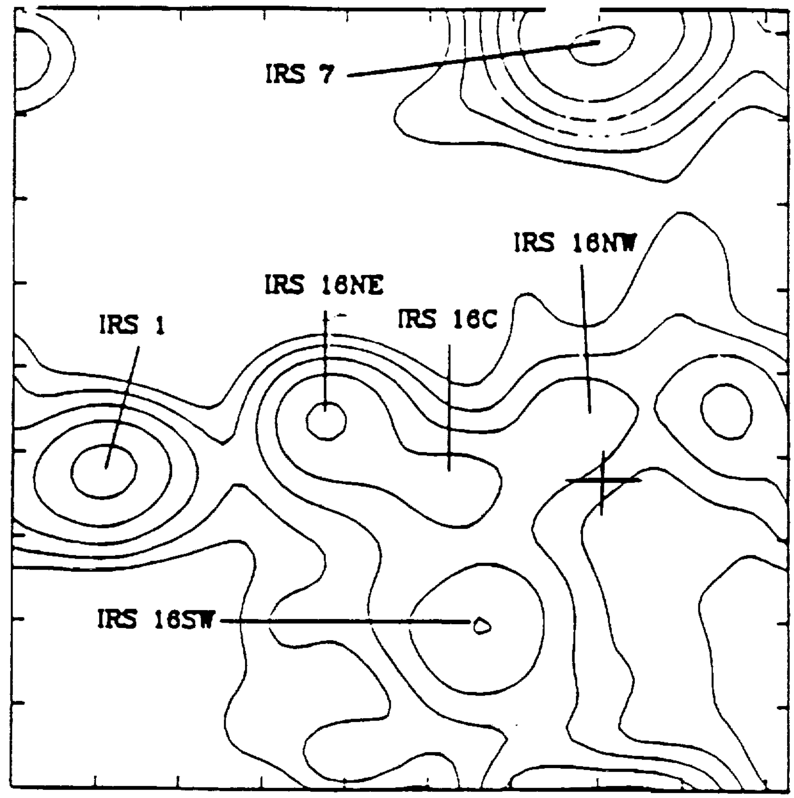


Figure 5. The position of Sgr A* (cross) superimposed on a 2.2 μm infra-red image of IRS16. Image from Capps *et al.*, 1987, reproduced from Simons, Becklin and Hodapp, 1989).

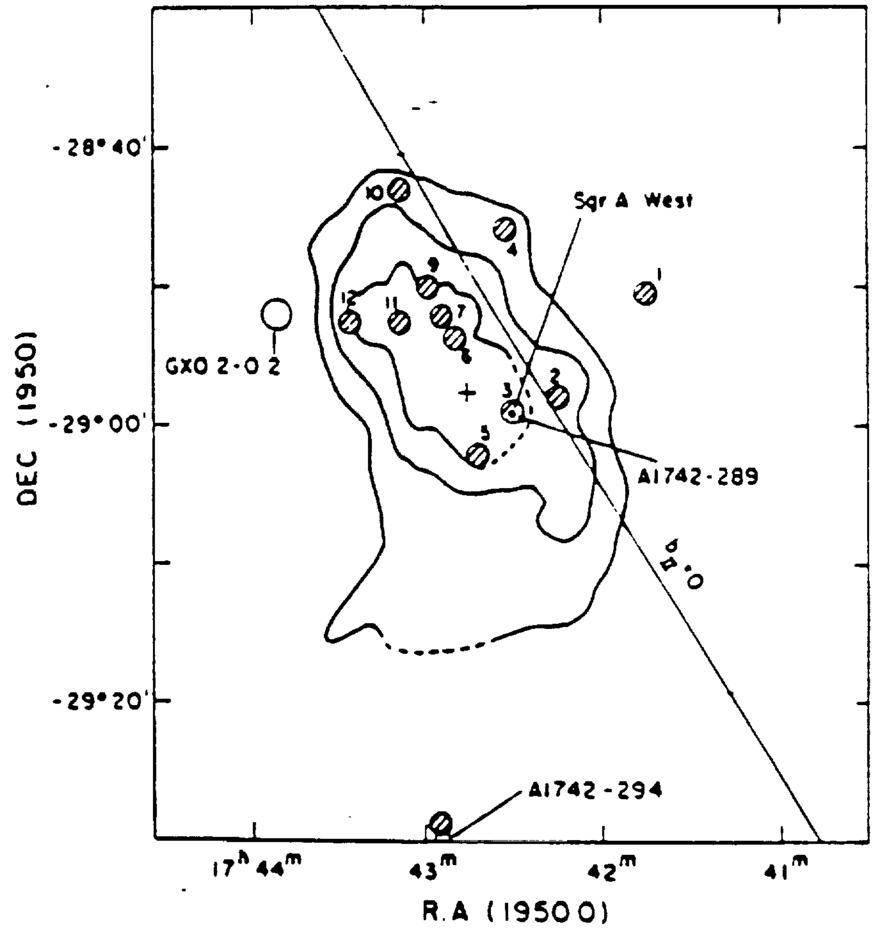


Figure 6. Schematic map of the *Einstein* observatory images of the galactic centre (Watson *et al.*, 1981). Numbered circles represent discrete sources with approximate 90where uncertain) indicate the diffuse emission.

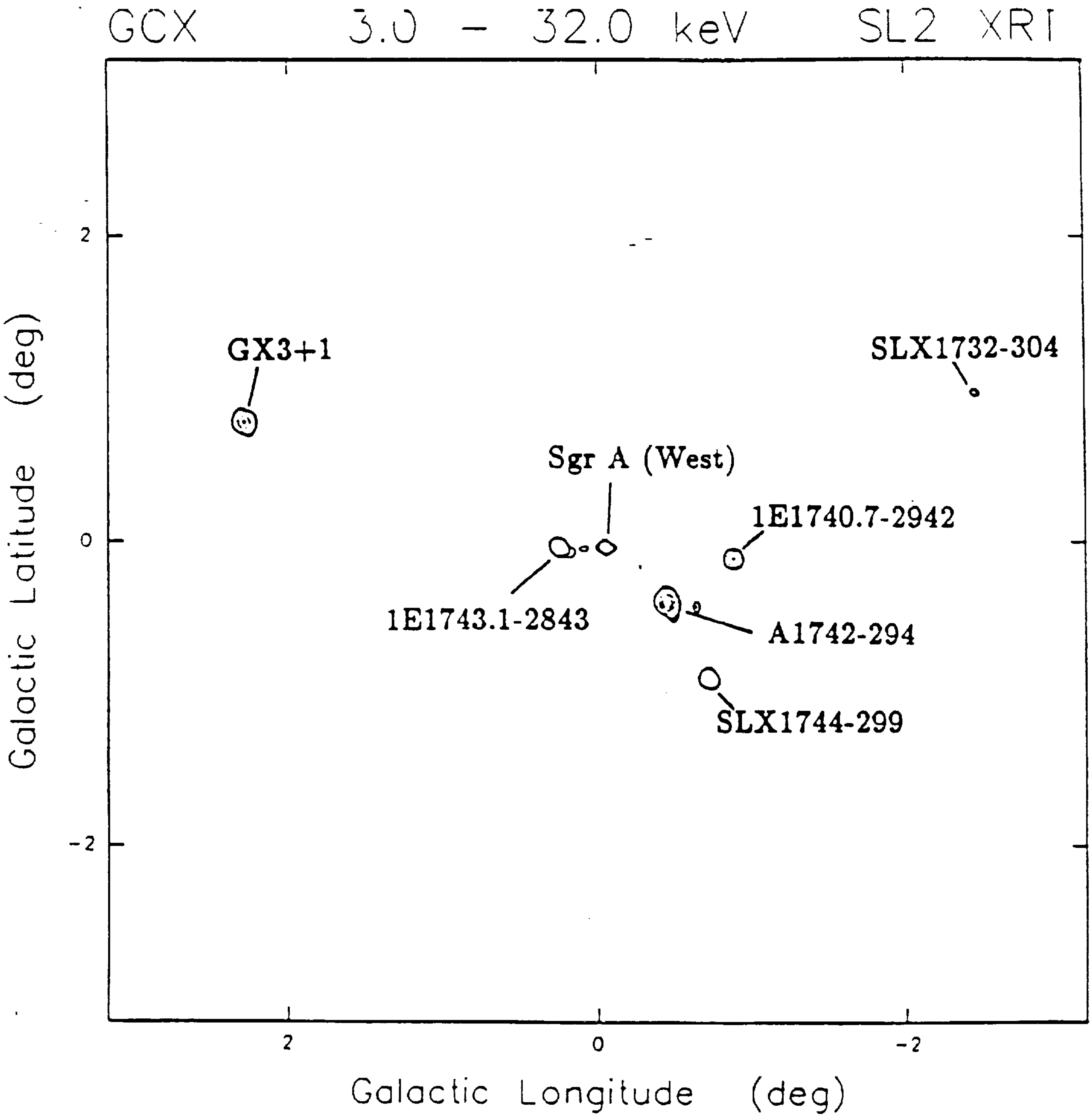


Figure 7. 3-32 keV x-ray image of a 6°square region around the galactic centre with 3 arcmin resolution obtained with the Spacelab-2 XRT. The source marked Sgr A (West) is consistent with either IRS16 or Sgr A*.

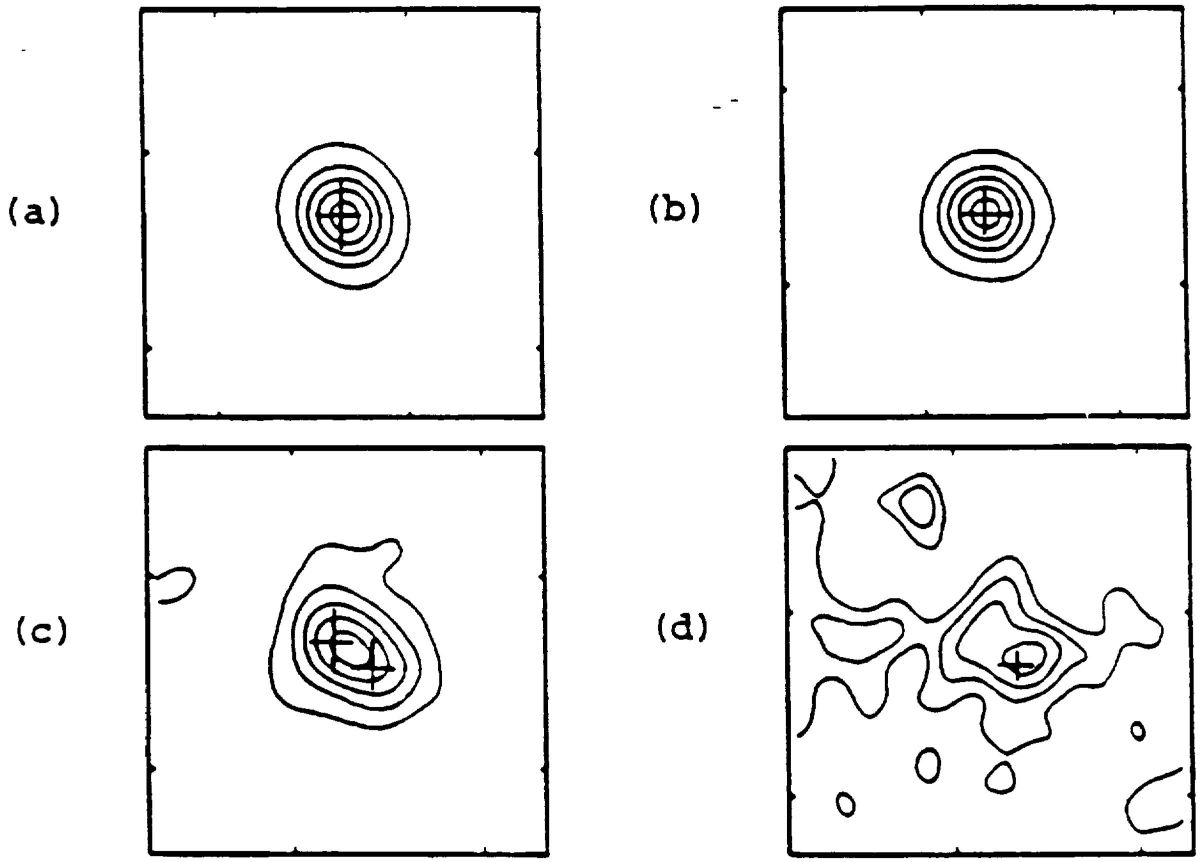


Figure 8. Enlargement of sources in Figure 7. The region shown is 22 arcmin in extent in each case. (a), (b) Point sources (A1742-294 and 1E1740.7-2942), showing the instrument resolution. (c) Two barely resolved sources (SLX1744-299, = SLX1744-299 + SLX1744-300) (d) The SGR A (West) source, showing possible signs of extension, although it should be noted the source is near the limit of detectability and is surrounded by diffuse emission. The cross shows the position of SGR A*. CASES will be ideally suited to elucidating the structure within (d) - the coarsest resolution is somewhat smaller than the size of the cross.

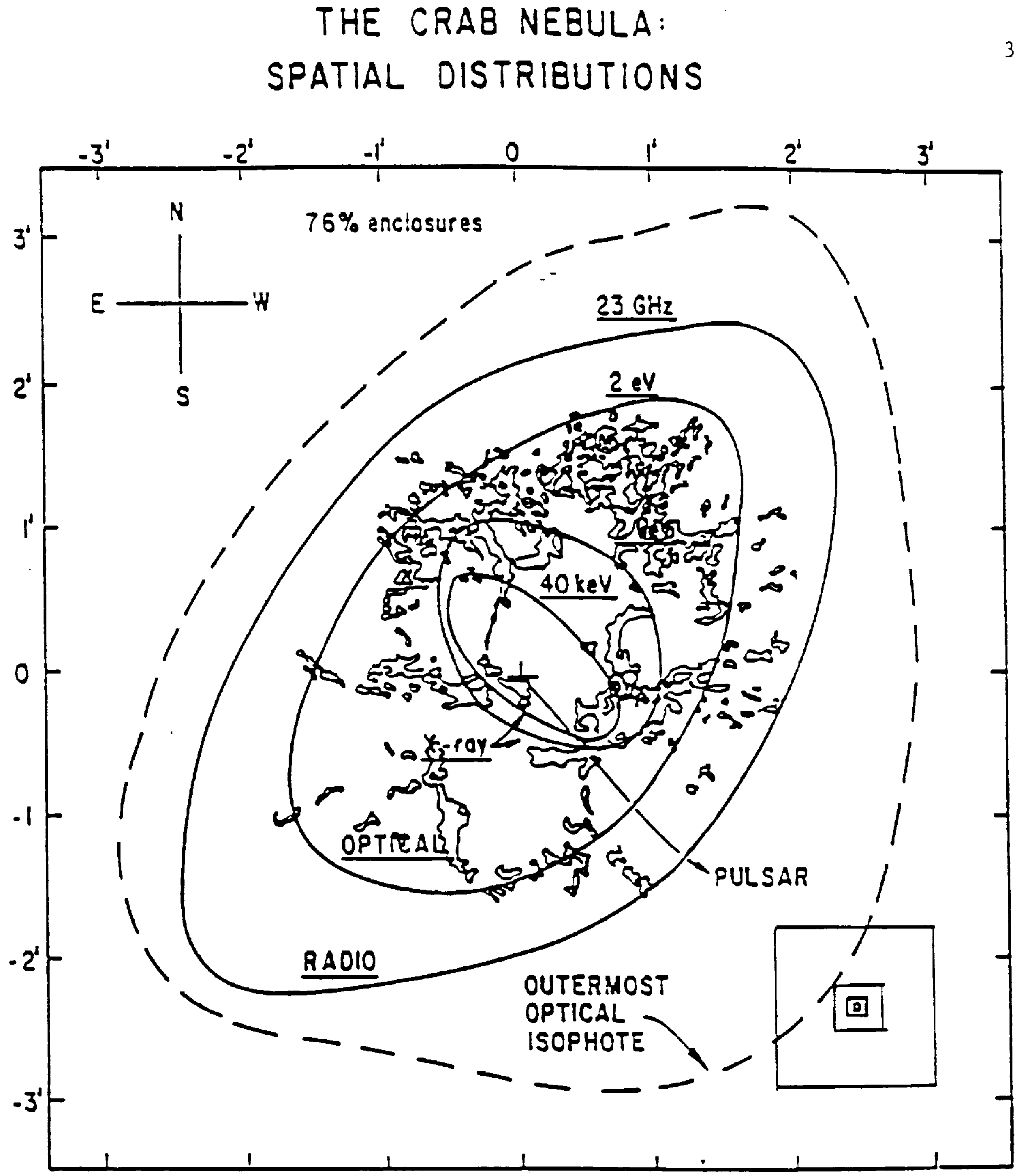
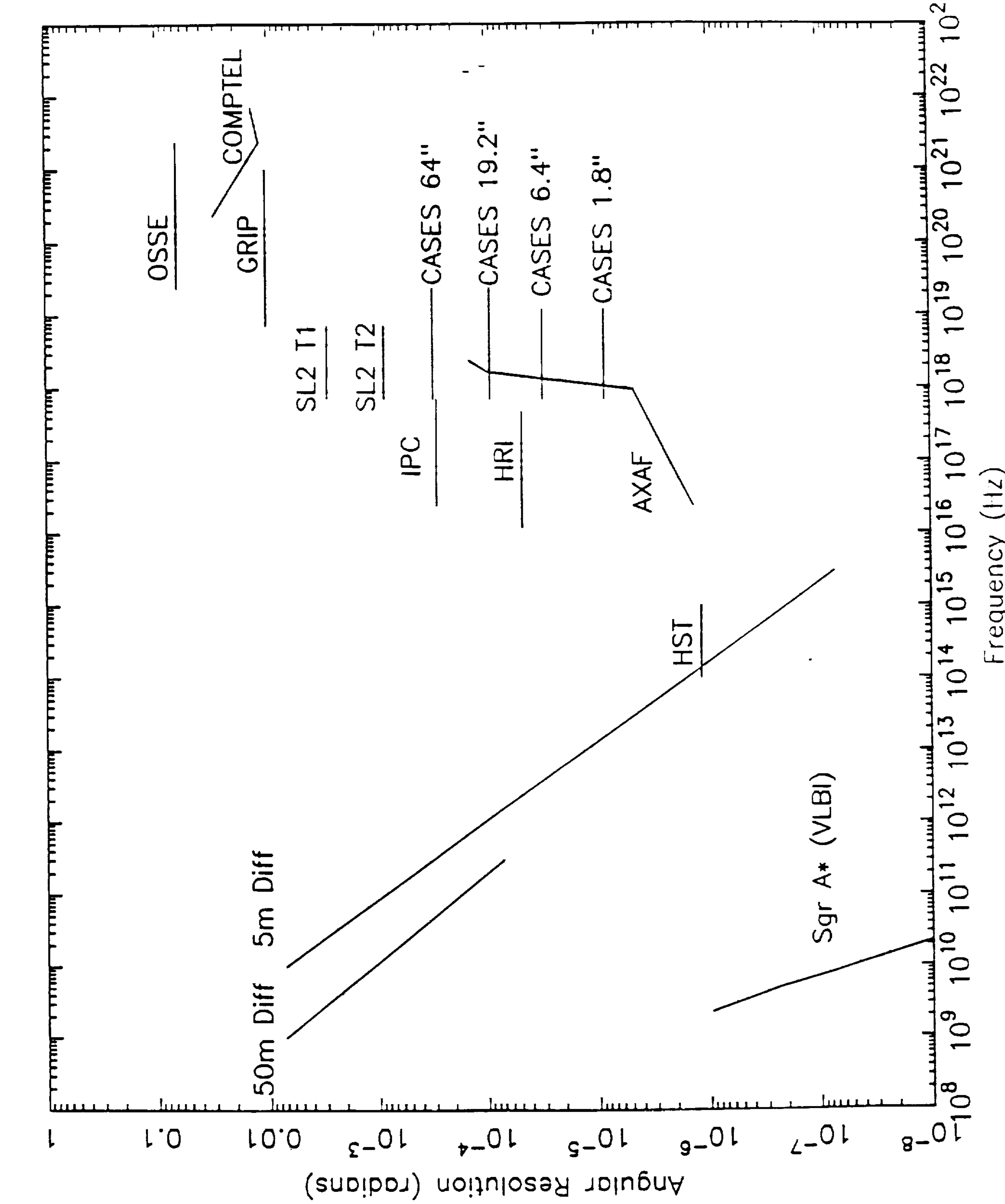
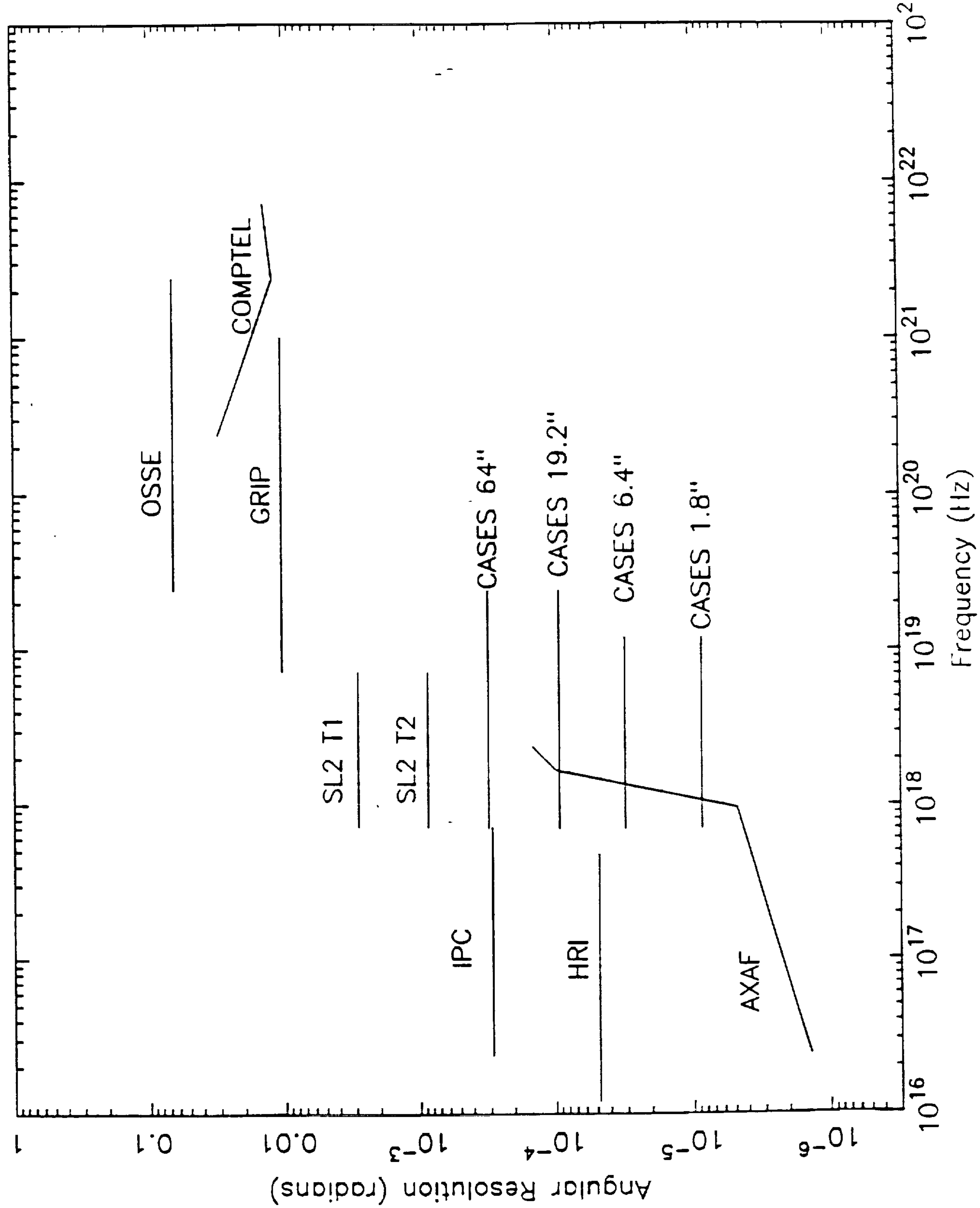


Figure 9. The extent of the Crab Nebula at different wavelengths. The oval-shaped curves enclose 76% of the nebula's emission at a given energy and follow iso-photal contours. The X-ray contours represent energies of 2 keV and 40 keV. (From Thesis of G.V. Jung). Squares show the proposed 64, 19, 6.4 and 1.8 arcsec resolutions of CASES.

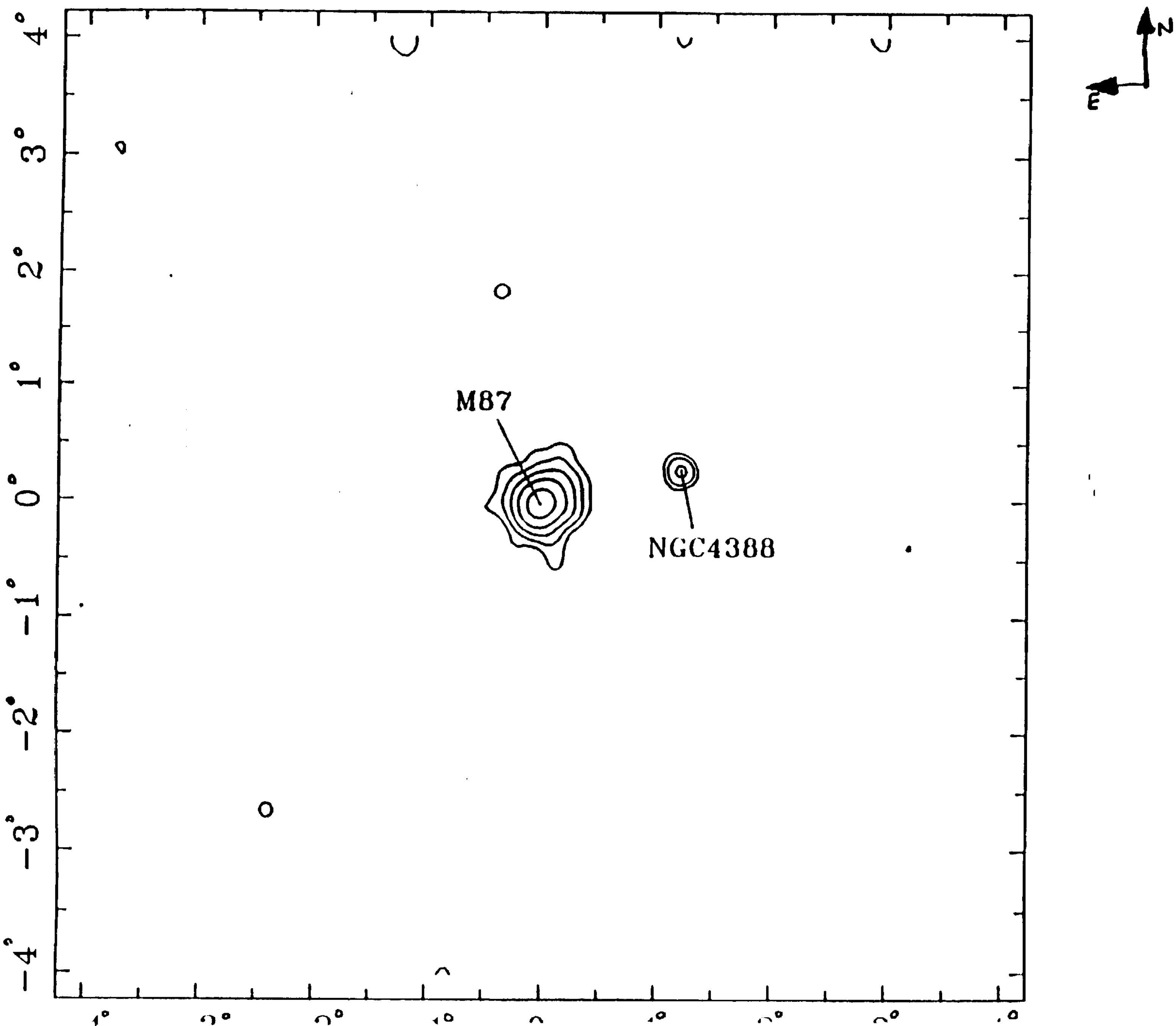

OSSE
COMPTEL
GRIP
SL2 T1
SL2 T2
CASES 64"
CASES 19.2"
CASES 6.4"
CASES 1.8"
IPC
HRI
AXAF
HST
50m Diff
5m Diff
Sgr A* (VLBI)
Frequency (Hz)
Angular Resolution (radians)



OSSE
COMPTEL
GRIP
CASES 64"
CASES 19.2"
CASES 6.4"
CASES 1.8"
SL2 T1
SL2 T2
IPC
HRI
AXAF
Frequency (Hz)
Angular Resolution (radians)
1
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}

	L_X (erg/s)
• Quasars	10^{44}-1
• BL Lacs	10^{44}
• Seyfert-1 Galaxies	10^{43}-1
• Seyfert-2 Galaxies	(10^{42})
• Mildly Active Galactic Nuclei	10^{38}-1
• "Normal" Galaxies	10^{35}

Virgo Cluster
2.0 – 19.6 keV



GALACTIC CENTRE

INFRA-RED & RADIO (LINE) OBSERVAT

SHORT λ – STAR DENSITY RISING TO CENTRAL (

COMPLEX OF SOURCES AT CENTRE (I

LONG λ – THERMAL EMISSION FROM HEATED

DUST IN A RING SURROUNDING

A CENTRAL DUST-FREE CAVITY

LINES – MOLECULAR RING

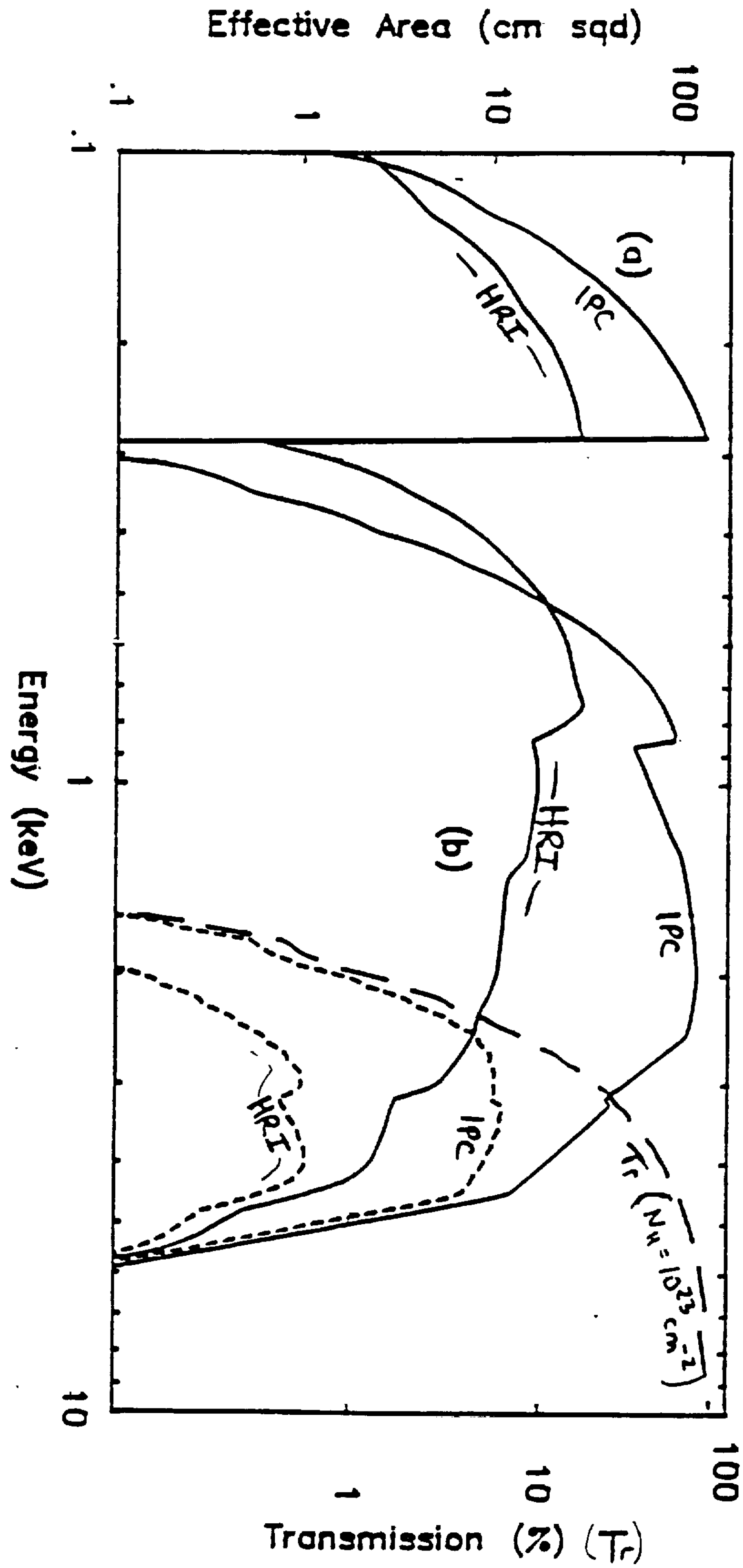
ROTATIONAL / STREAMER / TURBULENT MO

c.f BROAD LINE REGION

IN SEYFERTS

X- AND γ-RAY OBSERVATIONS OF THE GALACTIC CENTRE

	ENERGY	RESOLUTION
EINSTEIN	2 – 4·5 keV	1^{T} (+)
SPARTAN-1	2 - 10 keV	5^{T}
SPACELAB-2	3 - 30 keV	3^{T} / 12^{T}
GRIP	20 – 150 keV	50^{T}
VARIOUS	> 100 keV	$> 5^{\circ}$


Effective Area (cm sqd)
Energy (keV)
Transmission (%) (Tr)
(a)
(b)
IPC
HRI
Tr ($N_H = 10^{23}$ cm^{-2})

SGR-A* X-RAY LUMINOSITY

OBSERVATION	ENERGY BAND (keV)	L_x ERG. S^{-1} AT 10 kpc	NOTES
EINSTEIN OBSERVATORY	0.5–4.5	$1.5 \cdot 10^{35}$	ABS. COR
SPARTAN-1	2–10	$< 2.7 \cdot 10^{35}$	3σ UPPER LIMIT
SPACELAB-2	3–30	$6.2 \cdot 10^{35}$	
"	2–10	$3.5 \cdot 10^{35}$	EXTRAPOLA

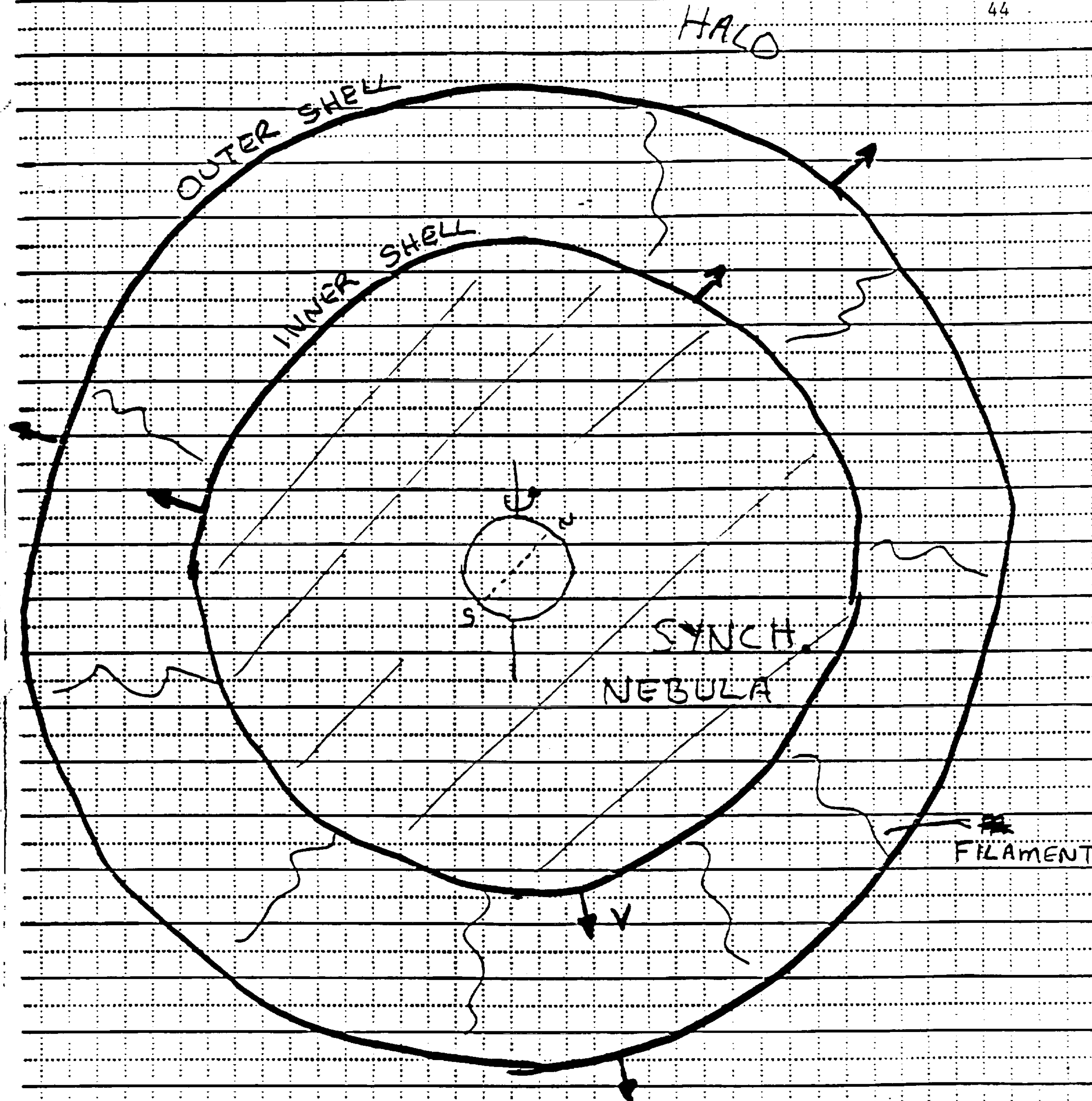
L_x (0.5–4.5 keV)

SGR A*	$1.5 \cdot 10^{35}$ erg s^{-1}
M31	10^{38} "
M33	10^{39} "
M100	10^{40} "
SEYFERT-2 s	$\sim 10^{42}$ *
SEYFERT-1 s	$10^{43} - 10^{44}$
QUASARS	$10^{44} - 10^{45}$

* CORRECTED FOR ABS.

	ENERGY	SIZE NE-SW	SIZE NW-SE	OFFSET	ELECTRC RANGE
Optical	2 eV	110"	160"	0	>100C
Einstein	1 keV	80	60	24±2	75
Balloon (Pelling et al)	30 keV	73	36	7±5	14
	50 keV	63	25		11

* $d = 2$ kpc
$B = 6.10^{-4}$ G



$R_{INNER} \sim 70'' \equiv 2$ light y.

$R_{OUTER} \sim 170'' \equiv 5$ light y.

$\frac{R}{V} = 850y$

cf $1989 - 1054 = 935y$

Appendix III

Working Group Meeting Agenda

CASES SCIENCE WORKING GROUP, FIRST MEETING
October 25 and 26, 1989
Agenda

Building 4481, Room 369

Wednesday, October 25, 1989

Morning: Introduction and Science Tutorials

9:00	Introduction/Concept	Davis/Hudson
9:30	NASA Comments	Hayduk/Share Kane
10:00	Solar Science Tutorial	Hudson
11:00	Galactic Science Tutorial	Skinner
12:00	Lunch	

Afternoon: Science-Related Technical Matters

1:00	Phase A Studies	Herrmann
1:30	Control/Dynamics Tutorial	Waites/Sharkey
2:15	Pointing Knowledge	General Discussion
2:45	X-Ray Counters	Ramsey/Weisskopf
3:15	X-Ray Optics	Hurford
3:30	Break	
4:00	Science Topics Flare Statistics Solar Shutter Observing Targets Extended Mission MMI (Moon/Mars Initiative)	General Discussion
4:30	Adjourn	
6:30	Group Dinner: Officers Club Prime Rib Special	

Thursday, October 26, 1989

Morning: Experiment Design

8:30	Discussion of Phase B Programs (Optional)	Haisch/Munro
9:30	CASES Evolution to P/OF	Dabbs/ McAnally (MDSSC)
11:00	CSI Laboratory Visit	Waites
12:00	Lunch	

Afternoon: Working Session

1:00	Working Session on Concepts Alignment Measurements Data Handling Science Data Plan	
3:30	Summary	Dabbs/Davis/Hudson
4:30	Adjourn	

Appendix IV

Working Group Membership List

CASES SCIENCE WORKING GROUP, FIRST MEETING
October 25 and 26, 1989
Sign-In Sheet

Name	Organization	Telephone #	Dinner # in Party
Brian Ramsey	MSFC / ES65	544-7743	—
Martin C. Weisskopf	MSFC/ES65	544-7740	2
Gordon Hurford	Caltech	818 356-3866	1
Gerry Skinner	University of Birmingham UK	UK 21-414-6450	—
Gerry Share	NASA/NRL	453-8547	—
Hugh Hudson	UCSD	(619)534-4476	1
Bernhard Haisch	Lockheed	415-424-3268	1
Ron Swinehart	Lockheed	205 722-4235	—
John Sharkey	MSFC/ED12	544-1437	—
Carmine De Sanctis	MSFC/PS02	544-0618	—
Karen McCoy	MDSSC/[illegible]	[illegible]	—
Jerry Hall	MSFC/JA53	544-1973	—
John Davis	MSFC/ES52	544-7600	1

CASES SCIENCE WORKING GROUP, FIRST MEETING
October 25 and 26, 1989
Sign-In Sheet

Name	Organization	Telephone #	Dinner # in Party
JONATHAN CAMPBELL	ES52	205-544-7076	
Wayne Bailey	TBE	(205) 726-5412	
S.T. Wu	UAH	895-6413	
Chuck Bower	ES65@MSFC	(205) 544-7744	
Connie Carrington	MSFC/PD12	544-4869	
Henry B Waites	NASA/MSFC/ED12	(FTS)824-1441 205 544 1441	
STEVEN P. JORDAN	BALL AEROSPACE	303-939-6239	1
RICHARD MUNRO	BALL AEROSPACE	303-939-6732	1
DAVE DOOLING	D^2 ASSOCIATES	852-7496	
SIMON SWORDY	UNIVERSITY OF CHICAGO	312-702-7835	
Kent Wood	Naval Research Lab	202-767-2566	
KEVIN HURLEY	UC BERKELEY SPACE SCIENCES LAB	415 [illegible] 9173	1
Joe Dabbs	NASA/MSFL PS02	(205) 544-0623	2

CASES SCIENCE WORKING GROUP, FIRST MEETING
October 25 and 26, 1989
Sign-In Sheet

Name	Organization	Telephone #	Dinner # in Party
Gordon Emslie	U. A. H.	(205)895/6167 /6173	?