Chapter 1

Observational Techniques

Key to our understanding of the physics at the center of the Milky Way and in particular the central compact radio source Sagittarius A* and its infrared and X-ray counterparts is our capability to gather observational data. These observations have to be carried out over a wide range of wavelengths and spectral resolutions in order to identify and analyze the relevant physical emission mechanisms. In order to distinguish between the contributions from different sources and to isolate Sgr A* from the surrounding stars, gas, and dust, it is necessary to achieve the highest possible angular resolution at each observing wavelength. In this chapter we describe how these measurements are done. We outline how the radiation is detected, what the technical requirements of the used instrumentation are, and how high angular resolution imaging and spectroscopy are performed. When explaining the general aspects in each spectral domain we put special emphasis on the case of the Galactic Center. This information may be particularly useful for understanding the observational results and the astrophysical interpretation put forward in chapters 2 and 3.

1.1 The GC Across the Electromagnetic Spectrum

Most of the information that is required to understand the physics of an astronomical target is obtained through electromagnetic radiation. The physics and technology involved in the detection of this radiation are quite different for the individual wavelength bands. In the following sections we cover some of the fundamental principles that apply to observations from the radio to the γ-ray domain.

1.1.1 *Radio Wavelengths*

Electromagnetic radiation from the longest wavelengths all the way into the sub-millimeter domain is usually detected with radio heterodyne receivers, that convert the received radiation to a lower, intermediate frequency using a stable local oscillator source. The detection takes place at the intermediate frequency. Bolometer systems allow a direct detection with large fractional bandwidth and become important in the mm to sub-mm regime (see following section). At the focus of a large parabolic mirror with diameter D the angular resolution A of the receiving systems at a wavelength λ is given via $A \sim \frac{\lambda}{D}$. For the currently largest single dish telescopes operating at the shortest radio wavelengths the angular resolution is limited to about 10 arcseconds.

For the Galactic Center such a resolution is sufficient to map the large scale distribution of the radio emission. A substantially higher angular resolution is needed if the fine structure of that emission or the direct environment of a compact source has to be investigated. This can be achieved by combining the output signals of an array of several individual antennas to an interferometer, where the highest angular resolution is determined by the longest baseline B as seen in its projection from the target source in the sky, rather than the diameter D of the telescopes which then defines the field of view (FOV) of the interferometer. Technical and physical concepts of radio interferometry are given in a number of review articles and text books (e.g. Fomalont & Wright 1974; Meeks 1976; Thompson *et al.* 1986). For the Galactic Center the technique of radio interferometry is indispensable for the investigation of structure on angular scales of a few arcseconds and below. Since this method is currently in the process of also becoming feasible in the infrared domain (first experiments on the Galactic Center are currently being conducted) we will now give a concise summary of the relevant facts.

The output of an interferometer is called the visibility function $V(u,v)$. Here u and v are are the orthogonal components of the two dimensional projection of a baseline for each telescope pair as seen from the target. The complex visibility function $V(u,v)$ is linked to the intensity distribution $I(x,y)$ on the sky via a Fourier relation:

$$V(u,v) = \int\int e^{-2\pi i(ux+vy)} I(x,y) dx dy \quad . \tag{1.1}$$

Mathematically the integral can be thought of as being carried out from

$-\infty$ to $+\infty$. However, due to the finite response of the primary beam and a limited sampling rate of the data, it is in practice only carried out over the solid angle of Ω_B of the primary beam or an even smaller region. Since $I(x,y)$ is a real function, V is hermitian and the following relation to its complex conjugate V^* holds:

$$V(-u,-v) = V^*(u,v) \quad . \tag{1.2}$$

The intensity distribution can be obtained via the inverse Fourier transform

$$I(x,y) = \int\int e^{2\pi i(ux+vy)} V(u,v) du dv \quad . \tag{1.3}$$

This means that at each position (u,v) the complex visibility function V represents a Fourier component of the source structure given by $I(x,y)$. Here the quantities u and v are spatial frequencies that are proportional to the angular resolution achieved by the projected baseline(s) of the interferometer. The integrals need to be carried out over the range covered by the u and v values. Unfortunately the coverage of visibility data in the u,v-plane is sparse since only a limited number of telescopes can participate in the measurement. For M discrete measurements of V this can be expressed using the weights w_j with j running from 1 to M as:

$$V(u_j,v_j) = V(u,v)w_j \quad , \tag{1.4}$$

with w_j=1 for $u = u_j$, $v = v_j$, and w_j=0 else. The measured intensity distribution is therefore given by

$$I'(x,y) = \sum_{J=1}^{M} V(u_j,v_j) e^{2\pi i(u_j x + v_j y)} \quad . \tag{1.5}$$

Since V is the product of two functions, the measured quantity $I'(x,y)$, also called the "dirty map", can be written as a convolution between the real intensity distribution $I(x,y)$ and the so called "dirty beam" DB:

$$I'(x,y) = I(x,y) \odot DB \quad . \tag{1.6}$$

Here $\odot$ denotes the convolution operator. The dirty beam is the interferometer response to a point source that results in a constant output signal for each telescope pair defining one interferometer baseline. Introducing a function $W(u_j^2 + v_j^2)$ to weight the contribution from the longest baselines, the dirty beam is given by

$$DB(x,y) = \sum_{J=1}^{M} W(u_j^2 + v_j^2) e^{2\pi i (u_j x + v_j y)} \quad . \tag{1.7}$$

$DB(x, y)$ consists of a central component and side lobes representing a more complicated response to a point source resulting from the insufficient coverage of the u, v-plane. The so called "clean beam" is in most cases constructed via a Gaussian fit to the central component of the dirty beam. Correspondingly the measured distribution $I'(x, y)$ is called the "dirty map". The desired true intensity distribution $I(x, y)$ can be obtained by deconvolving $I'(x, y)$ with $DB(x, y)$. Here $DB(x, y)$ can be determined from the u, v-plane coverage. The deconvolution is mostly done via an iterative subtraction of point source response functions $DB(x, y)$ and is then called "cleaning".

The resulting list of "clean components" is restored to a "clean map" by convolution with a "clean beam". There are "clean algorithms" of various complexity optimized to deal with large maps and extended structures for which the implicit assumption of a point source representation is not a good approximation. The quality of the map $I(x, y)$ also depends critically on the calibration of the complex amplitudes and phases of the visibility function, the phase calibration is especially problematic. The visibility phases carry, in addition to information on the source structure, information on the source position. For compact radio interferometer arrays the calibration can be tied to a common local oscillator signal. Very long baseline interferometry includes trans- and intercontinental baselines or even baselines to satellite antennas. Here the local oscillator signal is replaced by independent exact clocks and so called "closure quantities" between a minimum of three stations must be used for mapping (see the review articles mentioned before for details).

For the Galactic Center, radio interferometry is an essential observational method to study the emission on all scales. Deep and sensitive maps in the decimeter to short centimeter wavelength range are obtained with compact arrays like the Very Large Array (VLA). With more than 27 antennas the u, v-plane coverage is excellent and ideally suited to map for instance details of the gas streamers in the central parsec. The achievable dynamic range (intensity range between the brightest and weakest

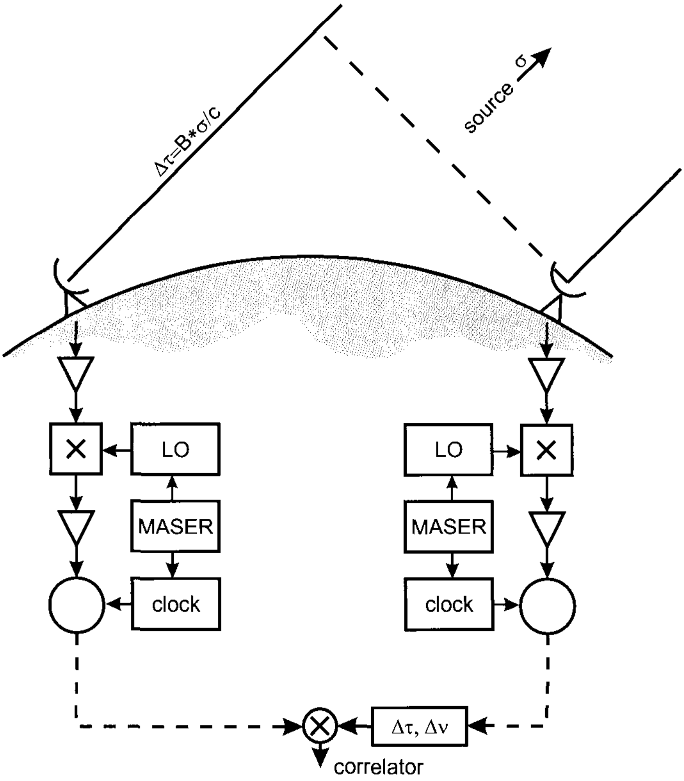


Fig. 1.1 Simplified schematic representation of a single baseline VLBI experiment. Each station, both of which define a baseline vector B, is equipped with an independent frequency and time standard (local interferometers share a common standard). The vector σ points towards the source. The amplified and digitized data stream is written to a storage medium and brought to a common location. Here the delay $\Delta\tau$ and Doppler shift correction $\Delta\nu$ is applied before the correlation. The resulting data stream (which is complex, since the correlation is also performed with a $\pi/2$ shift in one arm of the interferometer) contains the visibility information, i.e. Fourier amplitude and phase information of the source structure.

features that can be reliably detected) in the maps is, however, limited by the presence of the strong point source Sgr A* associated with the central massive black hole. At the longest wavelengths (e.g. 90 cm) the calibration is complicated additionally by the disturbing influence of the ionosphere on wave propagation. For radio interferometers operating in the (sub)mm-wavelength range the calibration must cope with similar problems due to the humid atmosphere.

Highest angular resolutions can be obtained using intercontinental baselines or even baselines that include satellite dishes. This Very Long Baseline Interferometry (VLBI; see Fig.1.1) involves radio and millimeter telescopes all over the world. The highest angular resolution for the Galactic Center can currently be achieved at wavelengths of 3 and 7 mm. With a FWHM (full width at half maximum intensity) of the beam of $\sim$100 microarcseconds the linear resolution at a distance of 8 kpc is 0.8 astronomical units, corresponding to about 14 times the Schwarzschild radius of a 3 million solar mass black hole or 124 million kilometers.

Most of the compact interferometers and single dish VLBI radio telescopes are located on the northern hemisphere. For the Galactic Center this means that the u, v-plane suffers correspondingly and that the final beam shape is elliptical with a lower angular resolution in north–south direction. Since the Galactic Center is located at a declination of about -29^o this also means that for observations from the northern hemisphere the source will always be at low elevations above the horizon. For the longest and shortest wavelengths phase and amplitude calibration due to disturbing influences of the ionosphere and atmosphere become especially demanding.

Millimeter arrays that are actively involved in observations of the Galactic Center are currently the Berkeley-Illinois-Maryland Association (BIMA) and the Owens Valley mm-array. Both arrays will form the new Common ARray for Millimeter Astronomy (CARMA) within the next few years. The Sub-Millimeter Array (SMA) will become of increasing importance for observing the Galactic Center. The SMA consists of eight 6 m elements that are reconfigurable to achieve baselines from 8 to 508 m (Moran 1998). The array is located on Mauna Kea in "Millimeter Valley", at an elevation of 4,080 m. It covers all bands from 180 to 900 GHz. The efficiency of the antennas is high: excluding the outer most 10 cm of the 3 m radius dishes to avoid edge effects, the average surface rms is 13 μm and for the inner 2.75 m radius that value is 12 μm. Zhao *et al.* (2003) report results from observations of Sgr A* at short-/submillimeter wavelengths made with the partially finished SMA on Mauna Kea. These observations resulted in the detection of three flares from Sgr A*.

In the mm and sub-mm domains further progress in dynamic range and sensitivity, as well as u, v-plane coverage and achievable angular resolution will be possible in the near future with the Atacama Large Millimeter Array (ALMA). Limited operation will start in 2006-2007. Located in the Atacama desert in northern Chile at an altitude of 5000 m an interferometer of 64 antennas with 12 m diameter each will allow for a typical resolution of 100 mas at 300 GHz in a 10" FOV (Field of View). The frequency range will be at least 100 (possibly 30) to 1000 GHz. Since the Galactic Center will culminate close to zenith at that location, ALMA will be an ideal instrument for this source. At longer radio wavelengths the Square Kilometer Array (SKA — at a not yet determined location) is planned and may lead to even higher dynamic range maps of the Galactic Center. The SKA will operate over a possible frequency range of 0.15 to ~20 GHz allowing for an angular resolution of 10 mas at 20 GHz and a FOV of the order of 1 degree at 1.4 GHz. Both ALMA and SKA could be used as phased arrays in mm- and cm-VLBI networks, which would improve high angular resolution radio interferometry for the Galactic Center considerably.

1.1.2 *Far-Infrared Wavelengths*

The far infrared (FIR) is probably one of the technically most challenging wavelength domains, but the development of detectors, cryogenic instrumentation, and the telescopes themselves make rapid progress. Between about 30 and 400 μm the Earth's atmosphere is opaque for radiation (Fig.1.2). FIR measurements therefore have to be carried out from high sites with low humidity, from airborne telescopes, or satellites. However, a major drawback — basically resulting from these technical restrictions — is the limited angular resolution in this spectral domain caused by the modest diameters of suitable primary telescope mirrors (e.g. 2.5 m in the case of the airborne observatory SOFIA).

For the Galactic Center this spectral range is of special interest since it allows one to trace the larger scale (typically in the ten to a few ten arcseconds range) distribution of warm and cold dust as well as the atomic neutral and partially ionized interstellar medium at and towards the center of the Milky Way. The primary temperature range of the gas and dust that is covered between 10 μm wavelength and the sub-mm domain stretches from about 300 K to a few Kelvin. The broad band spectrum of the central source Sgr A* peaks in the sub-mm/FIR domain and then falls sharply off towards the shorter wavelength infrared. Flux densities — or their limits — of Sgr A* are essential to study and distinguish between different emission processes.

In the near sub-millimeter wavelength range (a few 100 to 1000 μm) radio heterodyne techniques are applicable for high spectral resolution work. Schottky and SIS (Superconductor-Insulator-Superconductor) mixers are in use. This section of the FIR is also the range within which most bolome-

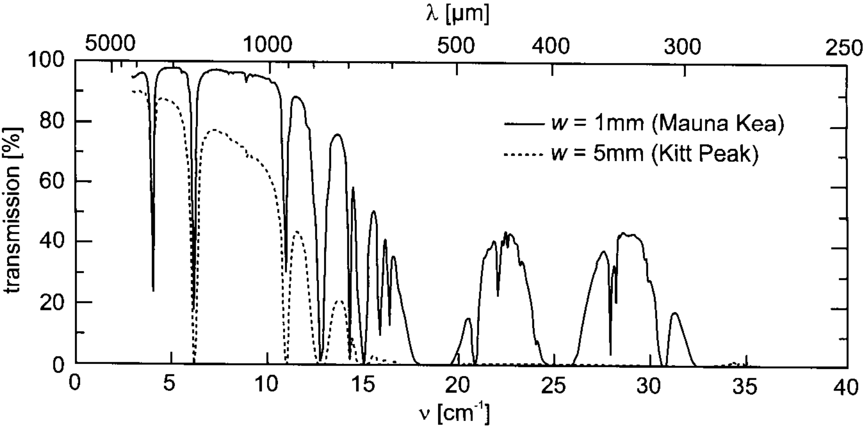


Fig. 1.2 The atmospheric transmission spectrum between 0.25 and 3 mm wavelength at the Mauna Kea and Kitt Peak sites (Griffin *et al.* 1986; Cox 1999). "w" is the precipitable water vapor at the sites. The graph demonstrates that — with the exception of two windows — the atmosphere is opaque shortward of 0.6 mm wavelength.

ters are operated. These devices absorb photons and convert them into heat and a corresponding variation in their electrical resistance.

The energy response of semi-conductors can be optimized for the deep FIR domain (a few 100 to about 30 μm) using the addition of impurities as well as the application of mechanical stress. This extends the operation of these extrinsic photo-conductors from the near- and mid-infrared to just beyond 200 μm wavelengths.

Bolometers and extrinsic photo-conductors can be used as broad band detectors or can be combined with Fabry-Perot interferometers to achieve high spectral resolution. In cases of high reflectivity and a low absorption coefficient of the detector material (e.g. in the case of Ge:Ga) each detector is located in an integrating cavity to maximize the quantum efficiency.

In the following paragraphs, we will give a brief overview of FIR observations of the Galactic Center.

Heterodyne measurements in the near sub-millimeter domain:

In the near sub-mm domain radio heterodyne techniques can be used to perform high frequency resolution measurements of selected lines. More recently such observations were performed during the austral winter seasons of 2001 and 2002 at the Antarctic Sub-millimeter Telescope and Remote Observatory (AST/RO). This station is located at 2847 m altitude at the Amundsen-Scott South Pole Station. Due to its very low water vapor, high atmospheric stability, and a thin troposphere the site is exceptionally well suited for sub-millimeter observations. AST/RO is a 1.7 m diameter, offset Gregorian telescope capable of observing at wavelengths between 200 μm and 1.3 mm (e.g. Stark *et al.* 1997, 2001). Simultaneous 461-492 and 807 GHz observations were performed using a dual-channel SIS waveguide receiver (Walker *et al.* 1992; Honingh *et al.* 1997) in order to study the distribution of warm molecular and atomic gas traced by the 461 GHz CO(4-3), 807 GHz CO(7-6), and 492 GHz [CI] lines in the inner 3 degrees of the Galactic Center area.

Bolometric measurements in the near sub-millimeter domain:

Near sub-mm bolometric measurements of the Galactic Center are possible from the ground. Chini *et al.* (1986) used the ^{3}He cooled MPIFR (Max Planck Institute für Radioastronomie) bolometer at a wavelength of 1.3 mm at the 3 m diameter IRTF (Infrared Telescope Facility) on Mauna Kea, Hawaii. These measurements resulted in a map of the large scale ($\sim$20'$\times$10') distribution of the cold dust. Zylka *et al.* (1995) used a single element ^{3}He cooled Ge:In:Sb bolometer at 800, 600, and 450 μm (UKT14 receiver Duncan *et al.* 1990) at the James Clerk Maxwell Telescope (JCMT) to determine the flux densities of Sgr A* and to discriminate its contribution from the cold dust distribution in the central parsec.

The SCUBA array was used to map the distribution of warm dust in the Galactic Center region (e.g. Pierce-Price *et al.* 2000). SCUBA (Holland *et al.* 1999) is a sub-millimeter continuum bolometer camera with two arrays. It is operated at the JCMT. One is optimized for 450 μm wavelength and has 91 pixels. A second array with 37 pixels is optimized for 850 μm. Both arrays can be used simultaneously. The angular resolution is 8" FWHM at 450 μm and 15" at 850 μm. It is usually operated in combination with a secondary mirror chopping between the source and the sky at a rate of a few Hertz.

SPIFI (Benford et al. 2003) is an imaging Fabry-Perot interferometer designed at Cornell University for use in the 350 and 450 μm telluric windows available on Mauna Kea as well as the 200, 350 and 450 μm windows available to the AST/RO telescope at the South Pole. The system employs a 5 $\times$ 5 array of silicon bolometers operated at a temperature of 60 mK using an adiabatic demagnetization refrigerator. SPIFI has been used to study the line emission of the molecular (the CO(7-6) feature at 371.651 GHz) and neutral atomic (the $^3P_2$-$^3P_1$ [CI] line at 370.415 GHz) gas phase in the central few parsecs — especially the circum nuclear ring (Stacey *et al.* 2004).

Staguhn *et al.* (2003) presented the first preliminary sub-millimeter continuum images of the Galactic Center region obtained with the new Caltech Sub-millimeter Observatory facility camera SHARC II (Dowell *et al.* 2003). The instrument allows observations at 350 μm wavelength with unprecedented sensitivity and instantaneous spatial coverage. SHARC II is a 12×32 high filling factor array of doped silicon bolometers each 1 mm×1 mm in size.

Continuum measurements in the deep FIR:

In this wavelength domain measurements are only possible from satellites or high altitude airplanes (or — mostly on larger angular scales — from balloons, which are not covered here). Werner *et al.* (1988) presented the first detection of linear polarization of the far-infrared (100 μm) emission from the about 3 parsec diameter dust ring surrounding the Galactic Center. The observations were carried out using the University of Chicago single-beam far-infrared polarimeter on board of the NASA Kuiper Airborne Observatory (KAO). Morris *et al.* (1992) used the array polarimeter STOKES on board of the KAO to measure the polarization of the 100 μm continuum emission at 14 positions in the dense, warm molecular cloud associated with the arched filaments near the Galactic Center.

Dust distribution, composition, and energetics of dust at the Galactic Center were studied via broad band continuum measurements in the 16 to 45 μm wavelength domain using instrumentation flown on the KAO (e.g., Rieke *et al.* 1978; Chan 1995; Chan *et al.* 1997; Telesco *et al.* 1995; Latvakoski *et al.* 1996, 1999). Far-infrared ~30 μm KAO continuum observations of the Galactic Center filaments, as well as the process of dust destruction in that region, are also discussed in Erickson *et al.* (1995) and Stolovy *et al.* (1995).

Spectroscopy in the deep FIR:

Deep FIR spectral line measurements towards the Galactic Center are well suited to investigate the interstellar medium in that region. Some of the brightest and most important cooling lines of the diffuse ISM are found in the deep FIR, e.g. the [CII] 158 μm and [OI] 63 μm fine structure lines. Measurements in this spectral domain reveal structure, temperature and density of the more extended atomic neutral and partially ionized gas component. Early spectrally resolved FIR measurements were obtained by Genzel *et al.* (1990) using the Mark II UC Berkeley cryogenic Fabry-Perot spectrometer (Lugten 1987) on the Kuiper Airborne Observatory (KAO). These measurements were continued with the MPE UCB FIR Imaging Fabry-Perot Interferometer using a 5×5 stressed Ge:Ga array (Poglitsch *et al.* 1991; Jackson *et al.* 1993). In addition the [OIII] 52 and 88 μm, [NIII] 57 μm, and [OI] 63 μm lines in the Radio Arc (Thermal Arches) regions of the Galactic Center (Timmermann *et al.* 1996) were mapped.

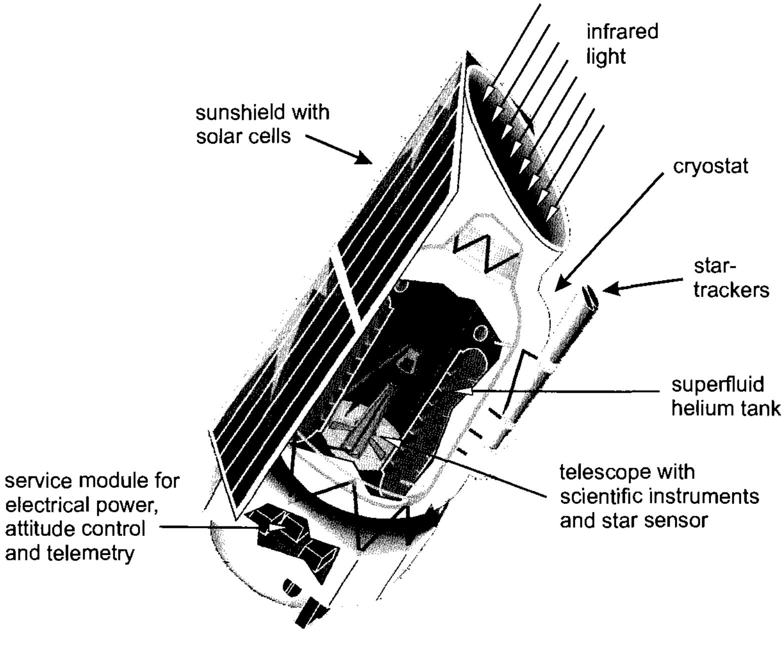


Fig. 1.3 Schematic drawing of the Infrared Space Observatory (ISO), launched in November, 1995, by the European Space Agency (ESA).

Further progress in terms of sensitivity, dynamic range, and angular resolution can be expected from future instrumental developments. As an example, the MPE built Far-Infrared Field-Imaging Line Spectrometer (FIFI LS; e.g., Looney *et al.* 2003) including for the first time at these wavelengths an integral field spectrometer, will be flown on board of the joint NASA/DLR airborne observatory *SOFIA*. It will be observing in the spectral ranges between 40-105 μm and 105-210 μm. The integral field unit consists of a reflective image slicer system that slices the 5×5 pixels field-of-view into a 25×1 pixels pseudo-long slit. The system therefore permits taking data cubes i.e. combined positional and spectral ($R = \lambda/\Delta\lambda = 1400$ - 6500) information.

Space projects:

Comprehensive information about the FIR spectrum towards the Galactic

Center was obtained using the spectrometers on-board of ESA's *Infrared Space Observatory (ISO)*, launched in November 1995 (see Fig.1.3). The measurements covered a wavelength range between 2.38 μm and 45.2 μm (SWS; Short Wavelength Spectrometer de Graauw *et al.* 1996a) and 60 μm and 168 μm (LWS; Long Wavelength Spectrometer Clegg *et al.* 1996; Swinyard *et al.* 1996). The observations gave information on the composition and extinction of the gas, dust, and ices within a few arcseconds diameter region towards the Galactic Center (Lutz *et al.* 1996; Lis & Menten 1998; Chiar & et al. 2001; Moneti *et al.* 2001; Rodríguez-Fernández *et al.* 2001).

The *Spitzer Space Telescope*, launched by NASA in 2003, carries out a galactic plane survey and a detailed, sensitive investigation of many nearby galactic nuclei. The results of these ongoing measurements will certainly have a deep influence on our understanding of the center of the Milky Way. The *Herschel Space Observatory* with its FIR cameras and spectrometers will allow for a broad range of opportunities to measure the continuum and line emission in the sub-millimeter and far-infrared domain. The Herschel Space Observatory is the 4^{th} cornerstone mission within the ESA HORIZON 2000 programme. The launch is planned for 2007. Three major instruments will be flown on Herschel: The Photoconductor Array Camera and Spectrometer (PACS) for medium resolution spectroscopy ($R=1\text{-}2\times10^3$) in the wavelength range 60-210 μm, SPIRE (Spectral and Potometric Imaging Receiver) a camera and low resolution spectrometer ($R=10^{2-3}$) for $\lambda>200$ μm, and HIFI, the Heterodyne Instrument for the Far-Infrared for high resolution spectroscopy ($R\sim10^7$) at wavelengths 127 $\mu m<\lambda<625$ μm. The goal of Herschel's mission will be detailed studies of the physics and kinematics of the interstellar medium in the gas layer within the central 50 parsecs, including outstanding gaseous components like the circum nuclear disk (CND), the arches, and radio filaments (see chapter 2).

1.1.3 *Near- and Mid-Infrared Wavelengths*

For the Galactic Center near-infrared imaging and spectroscopy of the wavelength range between 1 μm and 30 μm is of special importance. In the wavelength domain from 1 to about 5 μm sub-arcsecond angular resolution observations are possible, the extinction in that domain is more than ten times lower than in the optical, and at the same time it is the perfect window through which the bulk of the stars within the central stellar cluster can be observed. At wavelengths longward of 3 μm the emission of warm/hot dust becomes increasingly important. Observations of the motions and populations of the stars in the Galactic Center allow conclusions about the mass distribution and star formation history in that area. In order to achieve this goal infrared focal plane detector arrays with a fine pixel scale are required in order to obtain diffraction limited images using large apertures or interferometers. Here we give only a very short summary of the camera and detector requirements and a few aspects that are important for the Galactic Center.

Camera systems in that wavelength domain have to use either reflective optics (mirrors) or transmissive optics (lenses and windows) made out of materials which are highly transmissive in that spectral range (e.g. BaF_2 0.15–15 μm; KBr 0.23–25 μm; NaCl 0.21–26 μm; ZnSe 0.5–22 μm; ZnS 1.0–14 μm to name a few common ones; or special glasses). Optics and detectors have to be cooled to liquid nitrogen (77 K) or liquid helium temperature (4 K) in camera dewars, and the thermal heat load through the shielding and entrance window(s) must be minimized in order to keep the background low on the detector. Comprehensive information on these topics is given by Rieke (1994) and Glass (1999). Due to the variability of an increasingly brighter sky background at wavelengths longer than about 3 μm position chopping is required — preferentially with a fast telescope secondary mirror.

Between wavelengths of about 1 and 10 μm photodiode technology can be applied using HgCdTe, InSb, PtSi or other materials. With the application of anti-reflection coating, quantum efficiencies in the range of 90% and a read noise of about 10 to several 10 electrons can be achieved. Between 4 and 40 μm array detectors based on extrinsic silicon photoconductors or silicon blocked impurity band (BIB) detectors can be used. These devices have typical quantum efficiencies of 30-80% and read noise values of the order 50 electrons.

Very sensitive and increasingly large format near-infrared arrays have been built using Indium bump bonded hybrid technology (Fig. 1.4; see also reviews by Norton 1991; Scribner *et al.* 1991; Rieke 1994; Glass 1999; Amico *et al.* 2004). In these devices a monolithic infrared active layer made out of HgCdTe or InSb is contacted via small Indium bumps to a multiplexer unit. This unit is based on MOSFETs that can collect charge on their gate capacitors. The entire area over which the charge is collected defines a pixel. Pixel sizes are of the order of 40 μm diameter and the overall filling factor of the array with pixels approaches 100%. The pixels are made on a wafer of appropriate semiconductor substrates (multiplexer unit) and bonded with small Indium contacts to one side of the infrared detector

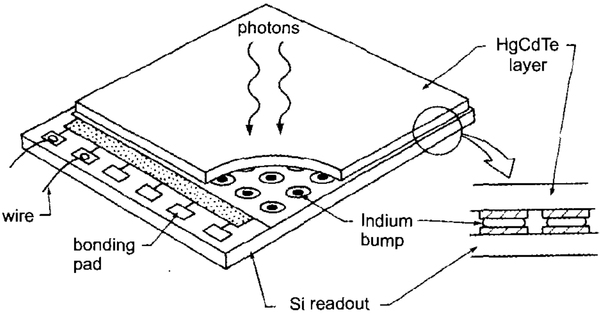
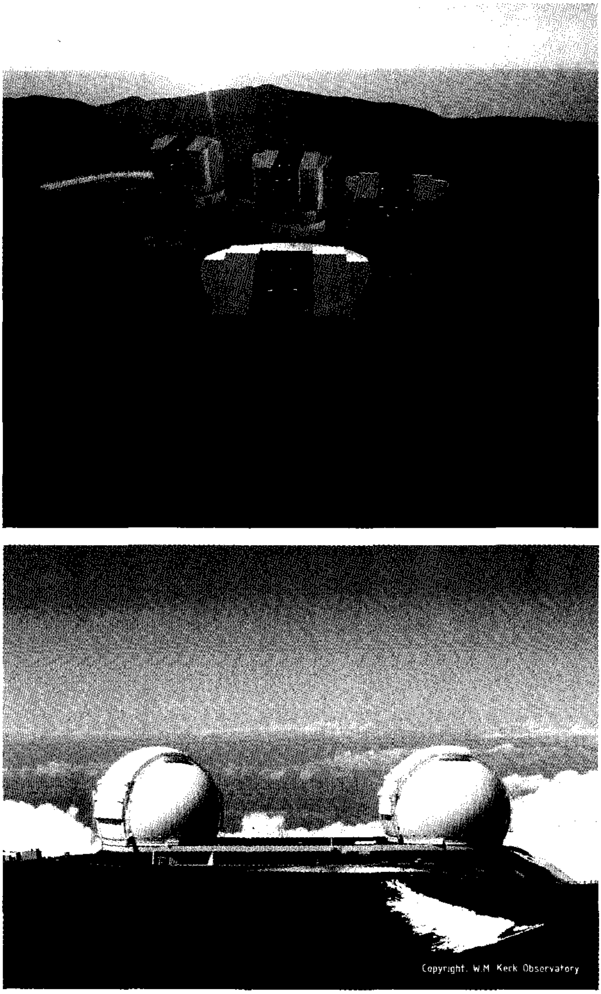


Fig. 1.4 The hybrid structure used for the Rockwell Hawaii 2 and ALADDIN arrays. The IR sensitive HgCdTe layer is bonded to the multiplexer unit via Indium bumps.

material. Therefore this material has to be illuminated from the back. The detector substrate must be thin enough (~10 μm) to let the created photo charge carriers migrate from where they have been produced to the gate capacitors as inputs for the readout electronics. Electronic switches can activate individual columns and rows such that individual pixels can be addressed. This random access mode allows any combination of sub-units of the array which will result in higher readout compared to the overall array. These hybrid arrays have been used for most of the telescope camera systems with which the Galactic Center has been observed to date.

The Galactic Center has been observed with the Hubble Space Telescope (HST) on a regular basis. The NICMOS (Near-Infrared Camera and Multi-Object Spectrometer) instrument was inserted into the HST in February 1996. It is equipped with three cameras with plate scales of 0.045"/pixel, 0.75"/pixel, and 0.2"/pixel. The cameras can be operated simultaneously, and a selection of filters, polarizers, and 3 slitless grisms for low resolution spectroscopy were in use. Especially in the 1-2 μm region, where HST's background is extremely low, the high sensitivity and very stable point spread function as well as the accessibility of the wavelength ranges between the atmospheric windows are a strength of NICMOS. These properties allowed for a variety of studies including sensitive searches for variable sources and accurate colors across the 1 to 2.5 μm region (e.g. Stolovy *et al.* 1999; Rieke 2003). Furthermore, its 0.2" pixel scale was very well suited for sensitive mapping of extended emission lines. High spatial resolution measurements of shocked molecular hydrogen lines have been carried out (Yusef-Zadeh *et al.* 2001). The atomic hydrogen Paα-line has



Copyright. W.M. Keck Observatory

Fig. 1.5 Images of the Keck and VLT sites. The ESO VLT (top) is located in Chile on Paranal in the northern part of the Atacama desert near Antofagasta. The site harbors four 8.4 m diameter telescopes (see *http://www.eso.org*). The Keck telescope (bottom) is located on Mauna Kea, Hawaii, consisting of two 10 *m* diameter telescopes (see *http://www2.keck.hawaii.edu*).

been used in combination with information from other wavelength domains to derive a high angular resolution extinction map for the central 3 pc of the Galactic Center (Scoville *et al.* 2003).

The angular resolution that can be achieved from the ground or from satellites is an important topic. The HST primary mirror has a diameter of 2.4 m. At a wavelength of 2.1 μm this results in a diffraction limited angular resolution of about 0.2". For investigations at higher angular resolutions, large ground-based telescopes like the ESO Very Large Telescopes or the Keck telescope (see Fig.1.5 and following sections) equipped with adaptive optics are currently best suited. From the ground the angular resolution of the observations is either determined by the atmosphere (in direct long exposures) or the diffraction limit of the primary telescope mirror (for speckle interferometric and adaptive optics observations). At a wavelength of 2.1 μm one obtains a resolution of about 45 milli-arcseconds (mas) with a 10 m class telescope. In order to achieve even higher angular resolutions telescopes have to be combined to near-infrared interferometers (see section 1.6.1).

1.1.4 *Optical Wavelengths*

The overall extinction toward the Galactic Center is large. Approximately 27 magnitudes of visual extinction correspond to a factor of 1.6×10^{11} by which the intensity of yellow, optical light at a wavelength around 550 nm that originates at the center is reduced. However, the situation improves dramatically towards near infrared wavelengths (see preceeding section), where the most sensitive observations can be done using charge coupled devices (CCD). These are arrays based on intrinsic silicon detectors in which the charges collected on a single pixel are electronically conveyed from pixel to pixel to a common readout amplifier outside the photosensitive array. Biretta *et al.* (1982) obtained direct CCD images and spectra at the 5 m Hale telescope. With two-color CCD observations of the Galactic Center region at 800 nm and 920 nm they confirmed the discovery of two very red optical objects by Grindlay & Liller (1978) that are located at an angular distance of only a few arcseconds from the non-thermal compact radio source Sgr A*. They refer to them as sources A and B (labeled "star 1" and "star 2" in Fig. 1.6). With optical spectra covering the wavelength range between 700 nm and 1000 nm, Biretta *et al.* (1983) could exclude that these objects are HII regions or compact star clusters at the Galactic Center. They concluded that these sources are most likely reddened foreground stars located a few kiloparsecs from the Galactic Center.

In the following years the Galactic Center area was observed at 1 μm both from the ground (Henry *et al.* 1984; Rosa *et al.* 1992) as well as using the HST (Liu *et al.* 1993). In addition to the foreground sources A and B

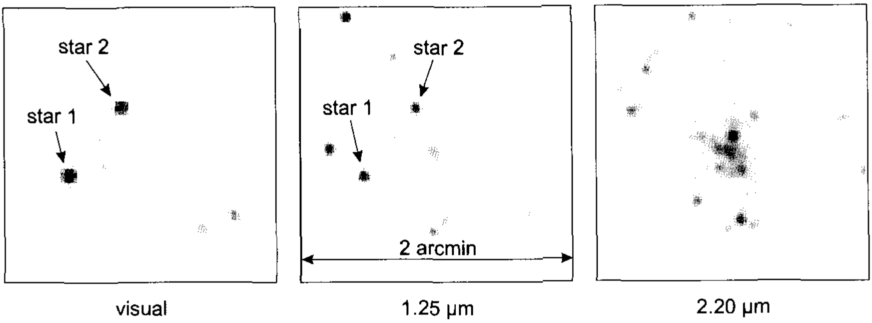


Fig. 1.6 Images of the central 2 arcminutes of the Galactic Center showing the effect of 27 magnitudes of visual extinction (source: Digitized Sky Survey). They show two stars (Biretta *et al.* 1982) that are suitable for optical wavefront sensing. Star 2 (USNO 0600-28579500) located 30″ NNE of the very center has an R-band magnitude of 13.2 (e.g. Ghez *et al.* 2003b).

(referred to as IRR1 and IRR2 by Henry *et al.* 1984), weak emission of quite a number of sources actually located within the central star cluster has been observed. Among them are IRS1, IRS21, IRS12, IRS7, as well as several of the extremely luminous blue stars in the IRS 16 complex. However, despite applying deconvolution algorithms (Rosa *et al.* 1992) a positive identification of the non-thermal radio source Sgr A* was not possible in this spectral domain.

Some of the stars that are detectable at visible wavelengths have become important for high angular resolution imaging as they are close to the position of Sgr A* and can therefore be used as adaptive optics reference stars.

1.1.5 *X-Ray Energies*

The X-ray emission from astrophysical objects can only be investigated above the Earth's atmosphere with X-ray telescopes on board of satellites orbiting the Earth. Some of the earliest X-ray observations of the Galactic Center region were done with the ROSAT satellite observatory (e.g. Predehl & Truemper 1994; Predehl 1995, and references therein). The most recent observations were done with telescopes on board of the NASA satellite Chandra and the European ESA satellite XMM-Newton (Fig.1.7). The telescopes of the satellite observatories consist basically of highly-nested, grazing-incidence mirrors (Wolter mirrors; Fig.1.8) which focus the X-ray radiation onto the image plane and the science instruments which detect and record the radiation. The exposures towards the Galactic Center are dominated by the diffuse emission of the Sgr A East region, which is thermal in origin and rich in emission lines. Collected by the mirror apertures the average combined count rates from that region are of the order of several events per second.

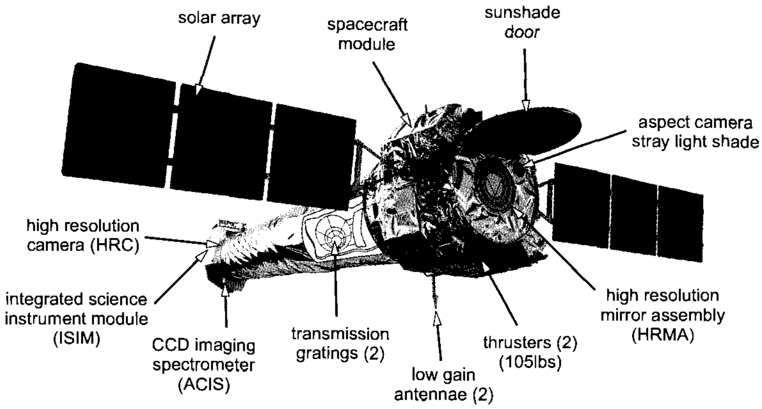


Fig. 1.7 The NASA satellite Chandra as an example of an X-ray observatory.

NASA's X-ray observatory Chandra was launched and deployed by Space Shuttle Columbia in July 1999. Chandra is on a very elliptical orbit around the Earth. The most distant point from Earth (apogee) is located at more than about one third of the way to the moon. The closest point to Earth on its orbit (perigee) is at a distance of about 16,000 kilometers. A complete orbit lasts for 64 hours and 18 minutes. This way the spacecraft orbit is optimized for maximum integration times above the belts of charged particles that surround the Earth. Uninterrupted observations as long as 55 hours (almost 180 kilo-seconds) are possible. The collecting area of Chandra's mirrors is about 400 cm^2 at 1 keV with an angular resolution of about 0.3 arcseconds.

Observations of the Galactic Center (e.g. Baganoff *et al.* 2001, 2003; Muno *et al.* 2003; Eckart *et al.* 2004a) were mostly carried out using two specialized CCD camera systems comprised of an imaging array (ACIS-I) and an element spectroscopy array (ACIS-S). Except for one, all of the detectors are front-side-illuminated CCDs operated at a focal plane temperature of -110^o C. Data frames are produced after an integration time of 3.2 seconds. A typical total integration time over which the data is collected is of the order of 50 ks. Each detected photon on the CCD chips results in a characteristic response covering several pixels. The Galactic Center is a weak X-ray source. Here the individual photon detection events are recorded as their pulse-height amplitudes of a 5×5 pixel region centered on each of the events. Some of the data analysis including the rejection of bad frames or unwanted cosmic ray events is done already on board of the spacecraft.

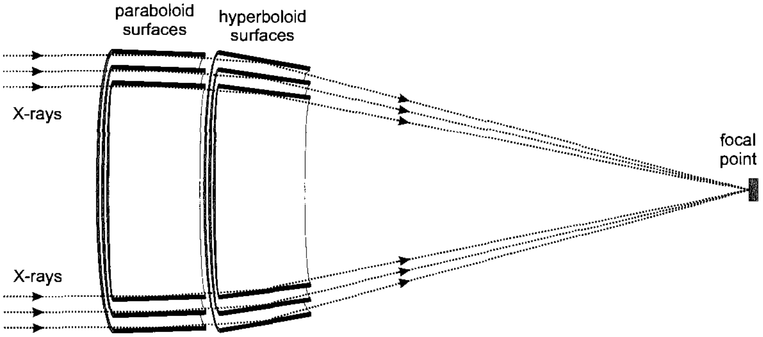


Fig. 1.8 A schematic view of a section of nested grazing-incidence Wolter mirrors as used in X-ray telescopes like Chandra and XMM-Newton.

The X-ray spectroscopy Multi-Mirror Mission (XMM-Newton) is one of the cornerstone projects in the ESA long-term program HORIZON 2000 for space science. The satellite observatory was launched on December 10, 1999, with an Ariane 5. The collecting area of the XMM mirrors is about 4300 cm^2 at 1.5 keV with an angular resolution of about ~5 arcseconds. The primary scientific objective of XMM is to perform high throughput spectroscopy of cosmic X-ray sources over a broad band of energies ranging from 0.1 keV to 10 keV. The XMM observatory includes three modules of type Wolter I (Fig.1.8), which are coupled to reflection grating spectrometers and X-ray charge-coupled device (CCD) cameras with energy resolving powers ranging from 10 up to 1000 as well as one small optical/UV telescope.

The European Photon Imaging Camera (EPIC) consortium has provided the focal plane instruments for the three X-ray mirror systems on XMM-Newton (Strüder et al. 2001, Turner et al. 2001). The EPIC focal plane imaging spectrometers use passively cooled CCDs to record the images and spectra of celestial X-ray sources focused by the three mirrors. There is one camera at the focus of each mirror; two of the cameras contain seven Metal Oxide Semiconductor (MOS) CCD cameras, while the third uses twelve PN CCDs, defining a circular field-of-view of 30' diameter in each case. Each EPIC instrument is equipped with a filter wheel that carries three kinds of X-ray transparent light blocking filters, as well as a fully closed, and a fully open position. Data processing on-board removes signal tracks caused on the detector by cosmic rays and generates X-ray event files for further data analysis. The instruments were calibrated on the ground using laboratory X-ray sources and in orbit using a variety of celestial X-ray targets. The current calibration is better than 10% over the entire energy range of 0.2 to 10 keV.

Since 2001 XMM-Newton repeatedly observed the Galactic Center detecting the onset of a flare (Goldwurm *et al.* 2003), and in October 2002, a powerful X-ray flare of Sgr A* which was about 160 times stronger than the quiescent level (Porquet *et al.* 2003).

1.1.6 γ-*Ray Energies*

In order to explore the nature of the central source Sgr A* it is of great interest to determine its flux density at the highest accessible energies. This can be achieved by γ-ray observatories orbiting the Earth. However, these energies are beyond the limit where mirrors can be used to focus the light onto the detector plane. In the domain of γ-rays, coded mask imaging is used — as briefly outlined below. As a result the current observations lack angular resolution in comparison to what is achieved in the X-ray or infrared/optical wavelength domains.

The EGRET instrument on the Compton Gamma-Ray Observatory has observed the Galactic Center (GC) region several times (Mayer-Hasselwander *et al.* 1998). A strong excess of emission is observed, peaking at energies >500 MeV towards the central position. However, a larger range of sources (including the very center) contributes to this emission.

The most recent results on the Galactic Center (Bélanger *et al.* 2004) have been obtained with the International Gamma-Ray Astrophysics Laboratory, INTEGRAL. INTEGRAL (Winkler *et al.* 2003) is a European Space Agency observatory that began its mission in October 2002 carrying four instruments. These consist of two main ones, IBIS (Ubertini *et al.* 2003) and SPI, the Spectrometer on INTEGRAL (Vedrenne *et al.* 2003), and two monitor instruments, JEM-X (Lund *et al.* 2003) and OMC (Mas-Hesse *et al.* 2003).

The IBIS coded mask instrument is characterized by a wide field of view (FOV) of $29^o \times 29^o$ ($9^o \times 9^o$ fully coded). From the event list for a given pointing, subsets of events are selected according to energy bins. Each subset is used to build a detector image or shadowgram generated by the source shining through a Tungsten alloy mask coded with a fixed pattern that has an area filling factor of $\sim$50%. Convolution of the shadowgram with the known decoding array gives rise to a sky image containing the main peak of all sources in the FOV and their secondary lobes. Source identification and subtraction of secondary lobes results in the final reconstructed sky image. The point spread function (PSF) has a beam width of 12' FWHM (full width at half maximum intensity). Fluxes are derived using INTEGRAL observations of the Crab Nebula. The system is sensitive over the energy range between 15 keV and 8 MeV. This response is achieved via two detector layers. One of these is a soft gamma-ray instrument with the upper CdTe layer sensitive between 15 keV and 1 MeV with peak sensitivity between 15 and 200 keV (ISGRI; Lebrun *et al.* 2003). The second, bottom CsI layer is sensitive between 200 keV and 8 MeV (PICsIT).

The Galactic Center was observed by INTEGRAL in 2003 between February 28 and May 1. The combined data cover a total integration time of about 1100 ks. Mosaicked images were constructed using data obtained with ISGRI in the energy ranges 20-40 and 40-100 keV.

The resulting final images give an unprecedented view of the high-energy sources of this region in hard X-rays and gamma-rays with an angular resolution of 12' (FWHM). Bélanger *et al.* (2004) report on the discovery of a source, IGR J1745.6-2901, coincident with the Sgr A* to within 0.9 arcminutes. Located at α_{2000}=$17^h45^m38.5^s$, δ_{2000}=-29^{o}01'15", the source is visible up to about 100 keV with a 20-100 keV luminosity of $(2.89 \pm 0.41) \times 10^{35}$ ergs s^{-1} (assuming a distance of 8 kpc). The new INTEGRAL source cannot be associated unambiguously with the Galactic Center. However, this is the first time that significant hard X-ray emission from within the inner 10' of the Galaxy has been reported. Therefore, a flux density contribution from the galactic supermassive black hole itself cannot be excluded.