Galaxy Structure

A very large body of information has been collected on the structure of the Galaxy. Here we can only concentrate on a small selection of the most recent and most important observational facts and theoretical findings. The MILKY WAY GALAXY belongs to the Local Group, a smaller group of three large and over 30 small galaxies, and is the second largest (after the Andromeda Galaxy M31) but perhaps the most massive member of this group. The Milky Way is most likely a BARRED SPIRAL GALAXY of Hubble type SBc. We are situated within the outer regions of its spiral disk, only about 14 ly above the equatorial symmetry plane but about 8 kpc or 26 400 ly from the Galactic Center (1 pc $\sim$ 3.29 ly $\sim$ 3 $\times$ 9.5 $\times$ 10^{12} km). The Milky Way forms a luminous band spanning all around the sky. This symmetry plane is also called the 'Galactic Equator'. In addition to the luminous stars there is also a dark band due to the obscuration of stellar light via gas and dust within the GALACTIC PLANE. The center of the Galaxy lies in the direction of the constellation Sagittarius, close to the border of both neighbor constellations Scorpius and Ophiuchus. The coordinates of the center (Rogers *et al* 1994) are $\alpha(2000) = 17^h\ 45^m\ 40.045^s \pm 0.010^s$ and $\delta(2000) = -29^\circ\ 00'\ 27.9'' \pm 0.2''$.

Main structural components

Since the Sun is located within the Milky Way disk it is exceedingly difficult to reliably determine its large-scale structure and dynamics, i.e. characteristics of the main components and the shape of the Galactic rotation curve.

The reason for that difficulty is mainly distance ambiguities and the location of the Sun within the Galactic obscuring dust layer. In summary the main structural components are the disk including the barred bulge with a central cusp, and most likely four spiral arms, a halo as well as a more extended corona including the Magellanic clouds and at least seven nearby dwarf galaxies and a large number of globular star clusters (see figure 1). The total mass of this central section of the Galaxy is (with separations from the center of ≤ 5 kpc) about 2×10^{11} solar masses ($M_\odot = 1.985 \times 10^{33}$ g). Here the molecular gas and dust as well as the youngest brightest stars of POPULATION I are located in a flat disk structure. The older population I stars form a less flattened distribution. This part of the Galaxy is surrounded by a probably ellipsoidally shaped halo of POPULATION II stars out to a radius of about 20 kpc. Population II stars are also found in the barred bulge of the Galaxy. The mass of this system is comparable with the mass in the inner section of the Milky Way. Within the halo the mass of the Galaxy amounts to about 4 $\times$ $10^{11} M_\odot$ (Fich and Tremain 1991). The Galactic Halo may have been formed largely by accretion and tidal disruption of satellite systems. This is supported by numerous observational facts: the discovery of a retrograde rotating stellar group, patchiness in the kinematics of halo stars (Majewski *et al* 1996), and the discovery of an elongated dwarf galaxy in Sagittarius (Ibata *et al* 1994). In addition most of the Milky Way satellites appear to be located near two great circles in the sky (Lynden-Bell 1976). The corona extends out to approximately 100 kpc and may account for as much as $(3–6) \times 10^{12} M_\odot$ (Fich and Tremaine 1991). It exceeds by far the mass contained in the spiral disk and bulge region.

Main tracers of structure and dynamics

The entire solar system is orbiting the Galactic Center at a distance of ~ 8 kpc, on a nearly circular orbit. It is moving at about 250 km s^{-1} toward $\alpha = 21^h\ 12^m$, $\delta = +48^\circ$ 19'. Figure 2 shows a rotation curve derived from observations and consistent with model calculations. At this velocity it takes about 220 million years to complete one orbit. The Sun has orbited the Galactic Center about 20–21 times since its formation about 4.6 billion years ago.

There is still a controversy on the shape of the rotation curve of the Galaxy in the deep halo. The rotation velocity may ultimately decay as in accord with the Keplerian law at a distance of 50 kpc. However, measurements indicate that the rotation curve of the Milky Way essentially stays flat. It actually may even still increase at the distance of the MAGELLANIC CLOUDS and the MAGELLANIC STREAM. Murai (1997) has clarified, on the basis of recent observational data on the spatial location of the LMC, SMC and the Magellanic Stream and their radial velocity distribution, that the halo of the Galaxy has a huge dark matter component that results in a flat rotation curve with a terminal velocity of the order of 250 km s^{-1}. However, for the spiral arms found outside the corotation of the bar, the dark halo may very well have some effect. In model calculations that include a halo component (e.g. Englmaier and Gerhard 1999; see below) resulting in a flat rotation curve, the halo contribution to the radial force at the solar circle is 23%.

The main tracers of the Milky Way structure are the stars and the line emission of the molecular (mostly traced via the line emission of the ^{12}CO $J = 1$–0 rotational transition at 2.6 mm) and atomic (traced via the 21 cm hyperfine-structure transition of atomic hydrogen—H I) gas in the disk. Through data from the Hipparcos astrometry satellite great progress has been made in understanding the stellar distribution and kinematics (e.g. Creze *et al* 1998; Bienaymé 1999). The stellar structure of the Milky Way can be investigated much better in the infrared light than in the optical, since the extinction is lower than in the visible light. The COBE satellite has provided an infrared image of the Milky Way's central region. The near-infrared (NIR) is a particularly
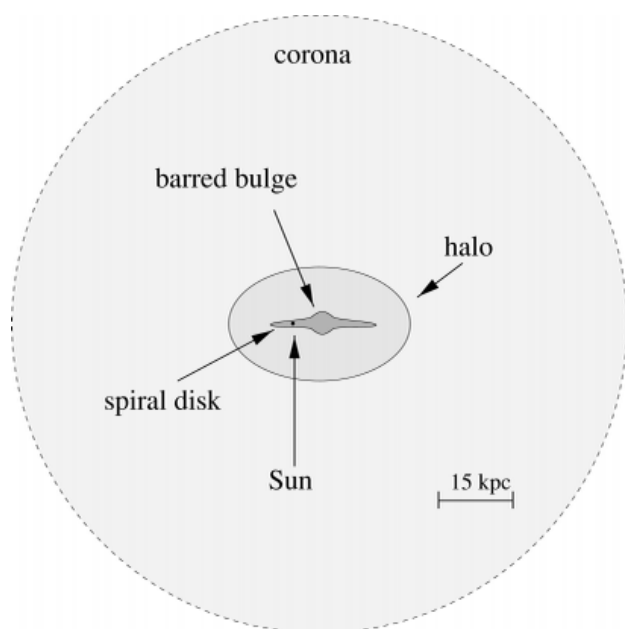
Figure 1. Main structural components of the Milky Way system. The Milky Way Galaxy in the center of the field is seen edge on from outside the corona that also contains the Magellanic Clouds, nearby dwarf galaxies and a large number of star clusters.
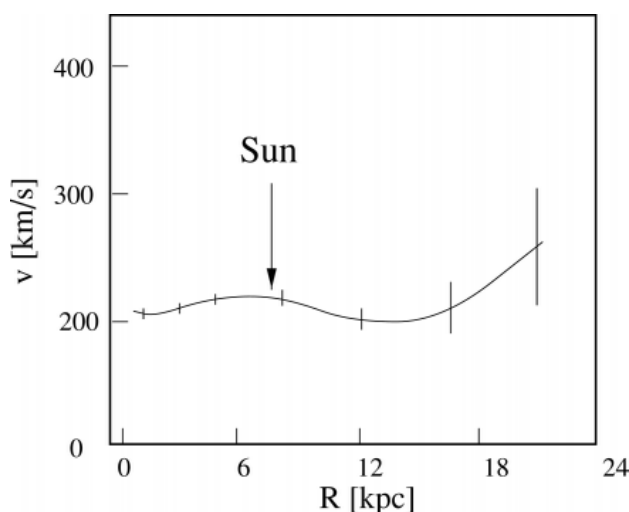

Figure 2. Rotation curve for the Galaxy (after Fich and Tremaine 1991). The vertical bars indicate the approximate uncertainty.

advantageous wavelength window for observing the distribution of old, evolved stars in the Galactic disk and bulge. These stars are important because they are tracers of the overall stellar mass distribution. At shorter wavelengths extinction is a serious problem, and at longer wavelengths the flux starts to be dominated by dust emission. As determined from NIR 2.4 μm mapping of the stellar continuum emission (Kent *et al* 1991) the radial surface brightness profile of the disk has an

exponential scale length of about 3.0 kpc. In the solar neighborhood, the scale height is about 250 pc and with increasing radius it decreases to about 160 pc at a distance of 5 kpc from the center. This is in agreement with star counts perpendicular to the Galactic plane.

The bar

In the last few years, independent evidence points to the existence of a bar in the inner Galaxy. This evidence results from NIR photometry (Blitz and Spergel 1991; Weiland *et al* 1994; Dwek *et al* 1995), from IRAS source counts (Nakada *et al* 1991; Whitelock and Catchpole 1992; Nikolaev and Weinberg 1997; Stanek *et al* 1997), as well as from the large microlensing optical depth towards the bulge (Paczynski *et al* 1994; Zhao *et al* 1996) and possibly also from stellar kinematics (Zhao *et al* 1994). This evidence is summarized in recent reviews, e.g. Gerhard (1996) and Kuijken (1996).

The best current models for the distribution of old stars in the inner Galaxy are based on the NIR data from the DIRBE experiment on COBE. The gravitational potential of the stars can then be connected with the available gas and stellar kinematic observations in order to study the large-scale structure and dynamics of the Milky Way Galaxy.

Since even at a wavelength of 2 μm the extinction towards the Galactic nuclear bulge is important, the DIRBE data has to be corrected for the effects of extinction. Spergel *et al* (1996) use a three-dimensional model of the dust distribution to clean the data. These data have then been used by Binney *et al* (1997) to fit a non-parametric model of the NIR emission under the assumption of eight-fold (triaxial) symmetry with respect to three orthogonal planes. The best fits to the photometry are obtained when the Sun is assumed to lie ~14±4 pc above the plane. For a fixed geometry the recovered emissivity is essentially unique (Binney and Gerhard 1996; Bissantz *et al* 1997). However, matching physical models are possible over the full range of likely bar orientation angles ϕ. This angle is defined as the angle in the Galactic plane between the major axis of the bar at $l > 0°$ and the Sun–center line. It covers a range from 15° to 35°. Using the most favored angle of $\phi = 20°$, the deprojected luminosity distribution shows an elongated bulge with axis ratios 10:6:4 and semimajor axis of ~2 kpc, surrounded by an elliptical disk extending up to ~3.5 kpc on the major axis and ~2 kpc on the minor axis. Figure 3 shows a comparison between the 3.4 μm flux density distribution as measured by the COBE satellite (full contours) and a model (dashed contours; Binney *et al* 1997) that assumes a bar angle to the line of sight of $\phi = 20°$. The asymmetry of the highest contours is a clear indication for the presence of a bar as seen from the position of the Sun within the Galactic plane. The enhanced flux at positive Galactic longitudes indicates the location of the tip of the bar that is closest to us.
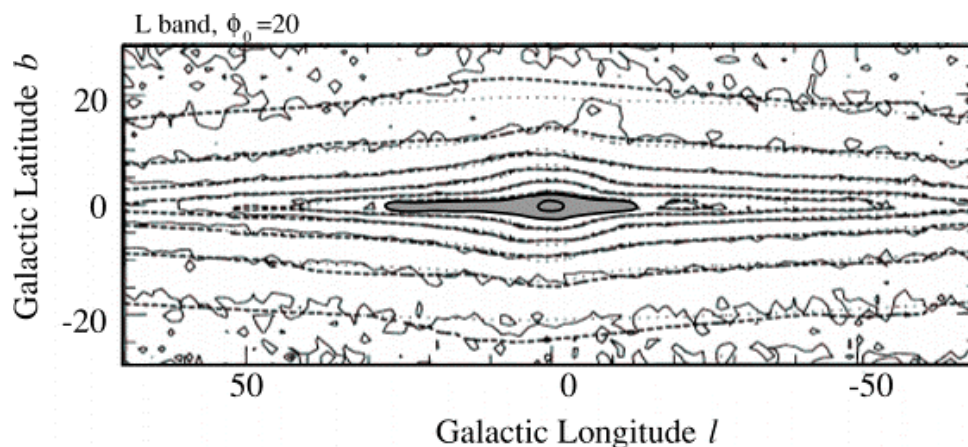
Figure 3. A comparison between the dust-corrected 3.4 μm flux density distribution as obtained by the COBE satellite (full contours, see also Arendt *et al* 1994) and a model (dashed contours; Binney *et al* 1997). In order to demonstrate that the Galaxy is not axisymmetric we filled in the top two contour lines.
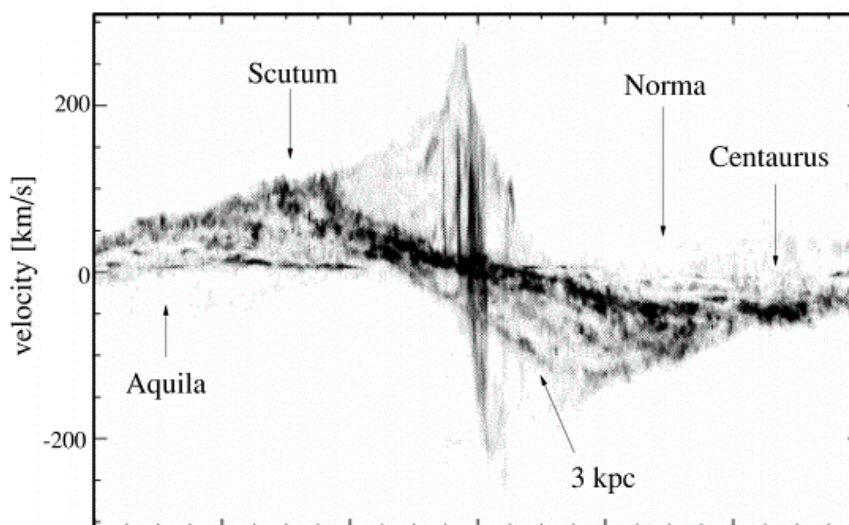

Figure 4. Galactic longitude velocity diagram of the ^{12}CO line emission as a function of Galactic longitude and velocity integrated over latitudes between $b = \pm 2°$ (Dame *et al* 2000). The directions of some arm tangents have been indicated. Comparison with figure 5 shows where the spiral arms are located within the Galactic disk.

In all models there is a local density minimum ~2.2 kpc down the minor axis. The subsequent maximum ~3 kpc down the minor axis may be associated with the Lagrange point L_4. The identification of this point as well as the length of the bar are consistent with a bar pattern speed of $\Omega_b \sim 60$–70 km s^{-1} kpc^{-1} (Binney *et al* 1997). Model calculations assuming an eight-fold or four-fold symmetry for the disk spiral structure indicate that the deprojected intensity distributions recovered from cleaned COBE data could reflect spiral structure within the Milky Way with density contrasts greater than ≥ 3 in the NIR.

The spiral structure

The SPIRAL ARMS can be traced by the distribution of atomic and molecular gas as well as the distribution of young bright stars and the emission line nebulae. The corresponding directions and distances with respect to the Sun can then be used to map out the local spiral structure. Figure 4 shows the distribution of the ^{12}CO line emission as a function of Galactic longitude and velocity integrated over latitudes between $b = \pm 2°$.

The spiral arms manifest themselves via an increase in projected density of brightness of the corresponding tracers especially when the line of sight is tangential to

the spiral arm. This technique was first applied to H I data (e.g. Kerr and Westerhout 1964) and has thereby led to a first picture of the distribution of atomic gas and a first indication of a spiral structure in the Galaxy. More recent modern H I surveys of the Galactic disk (e.g. Stark *et al* 1992; Burton 1985) primarily aim at high sensitivity, low contamination due to side lobes of the antenna beam and a large velocity coverage in order to trace the high-velocity H I gas located towards the center of the Galaxy and in individual clouds in and above the plane. Spiral arms are named after the constellations in which they are most prominent. The results indicate that the Sun lies near the inner edge of the so-called ORION ARM (see figure 5). The Perseus arm is located about 2 kpc beyond the Sun and the Aquila and Carina arm sections are approximately located at a distance from the Sun of 2 kpc towards the Galactic Center (see figure 5). From the study of H II regions, molecular clouds and the Galactic magnetic field it appears that the Milky Way may have four main spiral arms (Georgelin and Georgelin 1976; Caswell and Heynes 1987; Sanders *et al* 1985; Grabelsky *et al* 1988; Vallée 1995).

Dame *et al* (1987, 1999) have combined large-scale surveys of the ^{12}CO(1–0) integrated line intensity of the entire Galactic plane and specific nearby clouds to produce a panorama of the entire Milky Way in molecular gas at an angular resolution of $\frac{1}{2}°$. Their compilation exhibits a sky coverage and resolution which are comparable with those of early 21 cm surveys. A comparison with other population I tracers demonstrates that the currently available CO surveys probably provide an almost complete inventory of nearby molecular clouds. The ^{12}CO(1–0) line, however, traces in most cases the $\tau = 1.0$ surfaces of optically thick molecular gas. A much better census of the amount of molecular gas can be obtained via the optically thinner ^{13}CO(1–0) line. Stark (1987) presents a Galactic survey of 47 000 positions observed in the ^{13}CO(1–0) line emission. The data show a clear presence of voids in the molecular gas disk of the Milky Way. These regions contain many times fewer giant molecular clouds (GMCs) than do adjacent regions of similar size. This is interpreted as a signature of a spiral structure. The difference between the arm and interarm regions in the inner Galaxy is only clearly visible in the distribution of GMCs. Small molecular gas clouds are present throughout the disk. It is possible that GMCs are formed as interstellar gas enters a spiral arm and that they break up into small molecular or atomic clouds when the gas leaves the arm. The molecular gas disk is flatter than the atomic gas disk. The Gaussian scale height (i.e. thickness perpendicular to the plane) at the solar circle within 1 kpc is ~74 pc (Dame *et al* 1987). The H I atomic gas scale height is ~100 pc at 3 and ~220 pc at 9 kpc distance from the center (Malhotra 1995).
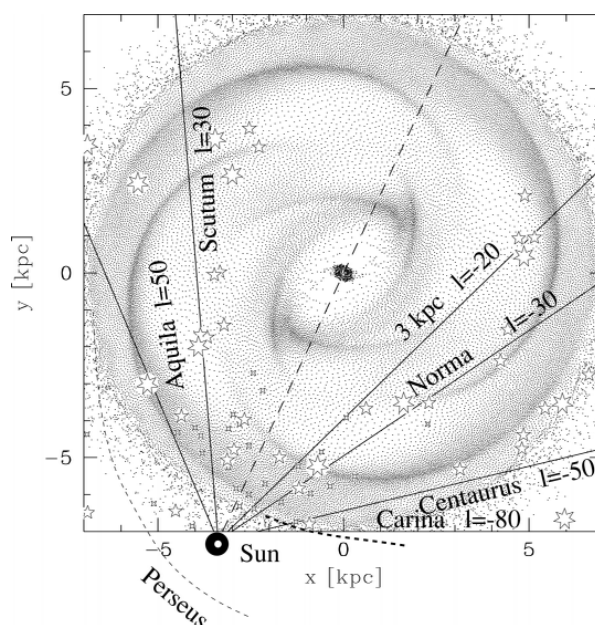

Figure 5. The gas flow in the Galactic disk under the influence of the barred bulge with a bar angle $\phi = 20°$, corotation radius at ~3.1 kpc as well as a dark halo component (Englmaier and Gerhard 1999). The location of the Sun is shown at $x = -2.7$ kpc and $y = -7.5$ kpc just outside the frame. The directions of some arm tangents and the corresponding approximate galactic longitudes have been indicated. The Orion arm is possibly a connection between the Aquila and Perseus arm in the vicinity of the Sun. The image is a result of hydrodynamical two-dimensional modeling using 20 000 particles in a smoothed particles hydrodynamics (SPH) code described in Englmaier and Gerhard (1997). The barred bulge has a size and orientation (4×2.4 kpc) which is almost identical to the central region void of particles.

The currently best model of Englmaier and Gerhard (1997) provides a coherent interpretation of most of the observed gas dynamical features. The four-armed spiral structure outside corotation reproduces quantitatively the five main spiral arm tangents at $l \le 60°$ that are observed in several tracers. In this model the observed 3 kpc arm is part of a spiral arm structure that starts at the ends of the bar and extends into the corotation region. Orbits along the bar are called x1 orbits. They allow transitions to the inner x2 orbits perpendicular to the bar (Contopoulos and Papayannopoulos 1980). This model exhibits an inner gas disk with a cusped orbit shock transition to an x2 orbit disk of radius $R \sim 150$ pc (see inner portion of figure 5). The corotation radius of the bar is fairly well constrained at $R \sim 3.5\pm0.5$ kpc. The Galactic terminal velocity curve from H I and CO observations out to $l\pm45°$ (~5 kpc) is approximately described by a maximal disk model with constant mass-to-light ratio for the NIR bulge and disk.

The center of the Galaxy

At a distance of only 8 kpc the Galactic Center is the closest nucleus of a galaxy, 100–1000 times closer than

the nearest extragalactic systems. It is thus a unique laboratory in which physical processes that are also relevant for nuclei of other galaxies can be studied with the highest angular resolution possible. The gas and dust on the line of sight to the center, however, make it impossible to observe it at optical or UV wavelengths. It is only accessible in the radio, infrared and x-ray domain. The optical extinction amounts to 30 magnitudes ($A_V = 30^{\mathrm{m}}$) or an attenuation of visible light by a factor of 10^{-12}. This corresponds in the NIR K band at a wavelength of 2.2 µm to an extinction of only $A_K = 3.3^{\mathrm{m}}$.

The central stellar cluster

Catchpole *et al* (1990) showed from NIR star counts that the density distribution of stars near the Galactic Center can be modeled as a power law r^{-p} with $p \sim 2.2 \pm 0.2$ for $K = 6^{\mathrm{m}}$–8^{m} stars. This is similar to the value of $p \sim 2.0 \pm 0.2$ derived from the distribution of OH/IR stars near the center (Lindqvist *et al* 1992). Using radial velocities of the OH–IR stars and the assumption of isotropy, Lindqvist *et al* determined the mass distribution inside ~100 pc. The corresponding mass density profile has $p \sim 1.5$ between ~20 and ~100 pc and steepens inside ~20 pc. The overall slope is in approximate agreement with the value of $p \sim 1.8$ originally found by Becklin and Neugebauer (1968). Because of the limited resolution the central cusp cannot be recovered from the DIRBE NIR data and has to be re-introduced to model the dynamics. The total mass, however, is small compared with the mass of the barred bulge. Inside the central parsec of the Galaxy the stellar number density counts show that all the ~ 600 stars in the central stellar cluster brighter than 16^{m} at 2.2 µm can be described very well by the number density distribution expected for an isothermal stellar cluster with a core radius of approximately 0.2–0.3 pc (Eckart *et al* 1993, Eckart and Genzel 1996).

Phenomena within the central few parsecs

The central few parsecs of the Milky Way is a region full of interesting phenomena (figure 6). A circumnuclear disk or ring consisting of a system of orbiting molecular filaments at a distance of 1.5–5 pc is connected to a dense central stellar cluster via several ridges, filaments and streamers of gas and dust that form the so-called 'mini spiral' close to the central compact (see above) stellar cluster that connects on large-scale NIR images visually to the stellar bulge and disk population at approximately the radius of the circumnuclear ring.

The circumnuclear disk is probably fed by gas infall from dense molecular clouds at distances larger than 10 pc from the center. The mini spiral represents the brightest part of the thermal radio source Sgr A (West). The central 1.5 pc is comparatively devoid of interstellar matter and is referred to as the central cavity. Right at the center of the stellar cluster there is located a compact radio source Sagittarius A* (Sgr A*) with a radio
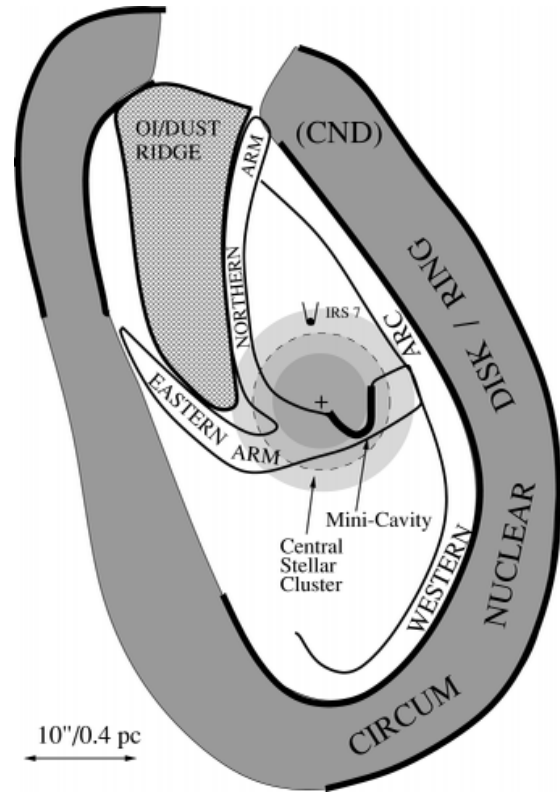

Figure 6. Schematic picture of the different structures in the Galactic Center. The 'mini spiral' arms—the eastern and northern arm as well as the 'bar'—connect the central stellar cluster region with the circumnuclear gas ring (after Genzel *et al* 1994). The brightest star at 2 µm wavelength, IRS 7 (infrared source), has been labeled. The position of the compact radio source Sgr A* is also indicated as a cross.

luminosity of ~2 × 10^{34} erg s^{-1}, corresponding to a flux density of 1.1 Jy at $\lambda = 2$ cm, and a size of less than 2.4 × 10^{13} cm (Rogers *et al* 1994; Krichbaum *et al* 1994). This source is the most likely candidate for a possible massive black hole at the center of our Galaxy (e.g. Rees 1984, Genzel and Townes 1987; Lo 1989). Along the arms of the mini spiral gas and dust are orbiting about the center where they interact with the intense nuclear wind originating from the central cluster of very massive and luminous stars. Recent subarcsecond angular resolution line imaging (Eckart *et al* 1995; Tamblyn *et al* 1996) and integral field spectroscopy (Krabbe *et al* 1995; Genzel *et al* 1996) have shown that several of the brightest members of the central cluster—the so-called IRS16 complex—are He I emission line stars. These objects show in their spectra prominent broad He I and H I recombination lines in emission. From non-LTE stellar atmosphere modeling of the observed emission characteristics of several of the He I stars Najarro *et al* (1994, 1997) have inferred that these objects are moderately hot (17 000–30 000 K), very luminous ((1– 30) × $10^5 L_\odot$) massive stars whose helium-rich surface

layers are expanding as powerful stellar winds with velocities of 200–800 km s^{-1} and mass loss rates of $(1–70) \times 10^{-5} M_\odot$ yr^{-1}. These stars have formed within the last few million years and provide the dominant fraction of the total luminosity of the central parsec. Imaging spectroscopy with the integral field imaging spectrometer shows that within the central 0.3–0.4 pc of the stellar cluster bright late-type stars (supergiants and the brightest AGB stars) are absent but that the core is surrounded by a ring of red supergiants–AGB stars showing strong CO band head absorptions in their NIR spectra (Genzel *et al* 1996; see also earlier work by Sellgren *et al* 1990; Haller *et al* 1996).

The central black hole
The gas and stellar velocities increase toward the position of Sgr A* indicating the presence of a large compact mass. The evidence for a dark central mass of $(1–3) \times 10^6 M_\odot$ in the Galactic Center has been steadily growing over the last two decades from observations of RADIAL VELOCITIES of gas and stars (Lacy *et al* 1980; Serabyn and Lacy 1985; Genzel *et al* 1985; Sellgren *et al* 1990; Krabbe *et al* 1995; Haller *et al* 1996; Genzel *et al* 1996). A reliable estimate of the enclosed mass and its compactness, however, can only be made if the full velocity field (radial and transverse components) is known. Furthermore, stars as tracers of the velocity field are much more reliable than gas, since they are not influenced by magnetic pressure or frictional forces. Using stars as tracers of the gravitational potential therefore allows us to measure the mass content and mass concentration within the central parsec of our Galaxy. Recent review articles on the phenomena and physical properties of the Galactic Center are Genzel *et al* (1994), Blitz *et al* (1993), Mezger *et al* (1996) and Morris and Serabyn (1996).

The stellar PROPER MOTION (Eckart and Genzel 1996; Ghez *et al* 1998) and radial velocity dispersions (Genzel *et al* 1996) are in very good agreement, indicating that the stellar velocity field is on average close to isotropic. Comparing individual images from different observing epochs one finds within the central arcsecond (0.04 pc) several fast-moving stars with velocities in excess of 1000 km s^{-1} in the immediate vicinity (0.01 pc) of Sgr A*. From the stellar radial and proper motion data, one can infer that a dark mass of $(2.61 \pm 0.35) \times 10^6 M_\odot$ must reside within about a light week of the compact radio source. Its density must be $2.2 \times 10^{12} M_\odot$ pc^{-3} or greater. There is no stable configuration of normal stars, stellar remnants (neutron stars or stellar black holes) or substellar entities that can account for the combination of both the high mass and the high mass density. The combination of these data—especially the proper motion measurements of the stars in the central

arcsecond—now provides compelling evidence for a massive BLACK HOLE at the core of the Milky Way.

In 2001 the Chandra X-ray telescope observed a flare of X-ray energy produced from where the lip of a supermassive black hole at the center of the Milky Way Galaxy should be. The flare dimmed and brightened over a period of ten minutes, the time taken for light to travel about 150 million kilometers, meaning that it originated from an object no larger in diameter than the distance of the Earth to the Sun. This implies that the mass at the center of our Galaxy (about 2.6 million times the mass of our Sun) is crammed into that space. According to the laws of general relativity, only a black hole can be that dense.

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Andreas Eckart

Peter Englmaier