THE CENTER OF OUR GALAXY: ACTIVITY AND HIGH-ENERGY EMISSION OF THE CLOSEST MASSIVE BLACK HOLE

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ABSTRACT

The Center of our Galaxy is a peculiar region where a number of crucial astrophysical phenomena take place, from star formation to SN explosions and accretion onto a massive black hole. The quest for a massive black hole in the Galactic Nucleus is of course of particular relevance because, it would be the closest of such extreme objects, which are now believed to reside in most of the galactic nuclei of the universe. I will review here the main observational characteristics of the Galactic Center with particular attention to the the problem of existence, physical condition and activity of the $3\ 10^6$ $M_\odot$ black hole coincident with the compact radio source Sgr A*. I will report historical and recent results of high energy observations of the central degree of our Galaxy, along with the specific accretion models proposed to account for the apparent lack of high energy activity from Sgr A*. The scientific perspectives of the next X and γ-ray missions in the domain of the Galactic Center physics are also mentioned.

Key words: Galactic Center; Black Holes; Sgr A*.

1. INTRODUCTION: THE NUCLEAR BULGE

Already in the decade 1920-1930 it was observed that the globular clusters are distributed with spherical symmetry around a point located in the Sagittarius constellation and also that stars were rotating around the same point of the sky. We now know that the dynamical center of the Galaxy is indeed located in Sagittarius, at about 8 kpc from the Sun, right in the middle of the Milky Way. The Sun also lies on the galactic plane and the Galactic Center (GC) is highly absorbed by all the galactic disk dust which intercepts the line of sight. Optical, UV and soft X-rays are therefore totally masked by an absorption of $A_V \approx 31$ mag corresponding to a column density $N_H \approx 6\ 10^{22}$ cm^{-2}, and the study of the central regions can be carried out only from radio to near infrared (NIR) frequencies or at energies > 1 keV. The recently published VLA pictures at 90 cm

(La Rosa et al. 2000) (Fig. 1) show the richness and complexity of the Galactic Center region. In the central 600 pc $\approx 4°$ (at 8 kpc $1'' \approx 0.04$ pc), a sky area often referred as the Nuclear Bulge, the interstellar matter (ISM) is concentrated in a narrow layer (50 pc) of molecular gas for a total mass of $\approx 10^8$ $M_\odot$. Half of this gas forms dense, cold Giant Molecular Clouds (GMC), the denser of which are Sgr B, Sgr C, Sgr D and those in the Sgr A complex. They have typical densities of $\approx 10^4$ -10^5 cm^{-3} and temperatures of $30-200$ K. Several Supernova Remnants (SNR) are visible in the picture along with other filaments and structures of non-thermal emission, like the prominent Radio Arc, a filamentary source crossing the galactic plane.

A number of thermal radio structures are also present, like the Bridge, which is connecting the Arc to the Sgr A complex. Some are identified with HII regions, like the features named Pistol and Seiklo, whose gas is ionized by young hot stellar clusters, like Quintuplet and Arches. Magnetic fields are strong (≈ 2 mG) compared to typical values of the galactic disk (≈ 10 μG) and lines are perpendicular to the galactic plane in the intercloud gas and parallel to the plane in the GMCs. Cloud kinematics indicates large velocity fields and a general inflow towards the center with rate of $\approx 10^{-2}$ $M_\odot$ yr^{-1}. Stellar content of the Nuclear Bulge is basically an extension of the Galactic Bulge population. It is dominated by a central nearly-isothermal cluster of low-intermediate mass stars, of metallicity ≈ 2, with density increasing towards the GC with decreasing radius as $R^{-1.8}$, from R ≈ 100 pc down to a core radius $R_c \approx 0.1$ pc where the star density reaches a constant value of $\approx 10^7$ $M_\odot$ pc^{-3} and the mass a core value of $M_c \approx 10^5$ $M_\odot$. However, unlike the Galactic Bulge, this old-middle age (1-10 Gyr) population coexists with a young (10^7-10^8 yr) population of massive stars whose total fraction increases towards the center and whose presence indicates recent star formation.

In the following I will describe results obtained for the inner 50 pc and from high energy observations of the central degree. For extensive reviews see Mezger et al. (1996) and Morris & Serabyn (1996), while for recent results see Vol. 186 of ASP Conf. Series (eds. Falke et al. 1999) and Yusef-Zadeh et al. (2000).
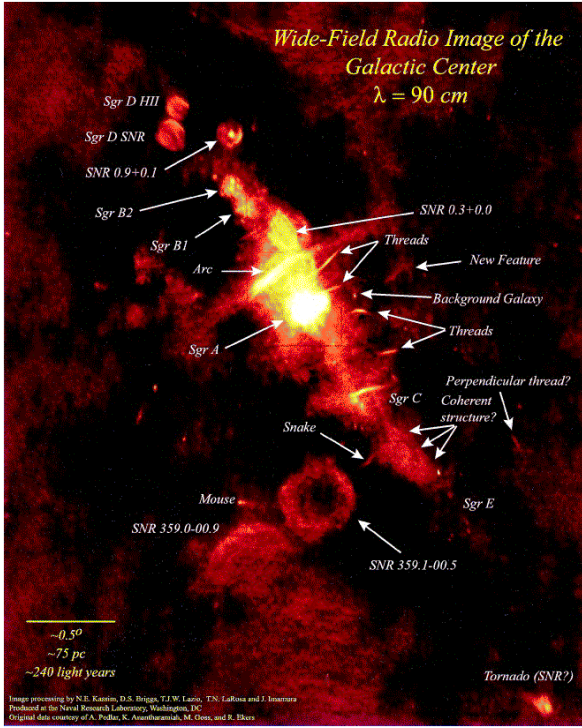
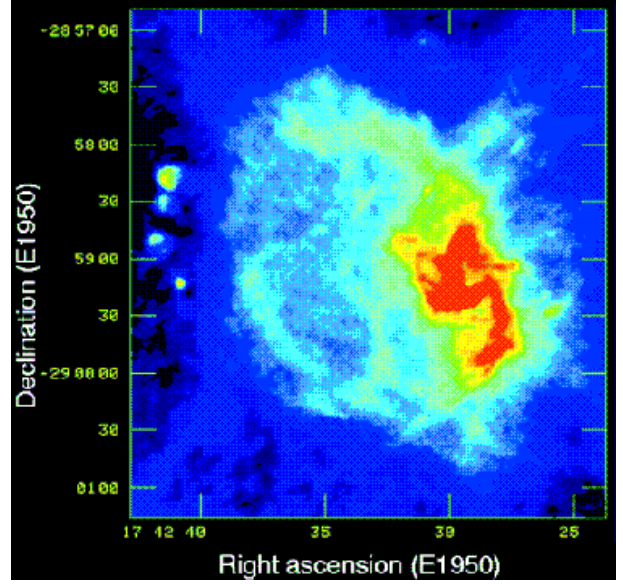*Figure 1. Very Large Array (VLA) image at 90 cm of the Nuclear Bulge.*

Figure 2. VLA (6 cm) images of Sgr A East halo (blue) and shell (light blue), the inner thermal minispiral (red) and the 4 HII regions on the East side.

2. THE SGR A RADIO AND MOLECULAR COMPLEX

The central 50 pc ($20'$) are dominated by the Sgr A radio complex (Fig. 2, from Yusef-Zadeh et al. 2000). Relevant components of the Sgr A complex are, listing from the outside to the inner regions: several dense molecular clouds, the non-thermal Sgr A East source, the CircumNuclear Disk (CND), the thermal source Sgr A West and the compact source Sgr A*. A recent study of molecular gas velocities of the region (Coil & Ho 2000) describes the morphology and distribution of matter of the complex. Two dense molecular clouds account for most of the ISM of the region, interact with, and probably supply matter to the inner central region. M-0.02-0.07, also known as the 50 km s^{-1} cloud, lies on the north-east side of the GC and includes the Sgr A East Core very dense MC (15 pc size and $2\ 10^5$ M$_\odot$ mass) observed to surround Sgr A East from behind the GC. It is connected by a molecular ridge to the North side of the other cloud, M-0.13-0.08 (the 20 km s^{-1} cloud), which is located South-East of the GC, about 10 pc in front of it and which seems to supply the CND of molecular gas through the so called "southern streamer". M-0.02-0.07 and its molecular ridge are compressed by the expanding shell of Sgr A East. Sgr A East is a non-thermal source composed by a diffuse halo of triangular shape ($7' \times 10'$) and an oval shell (7 pc $\times$ 9 pc i.e. $3' \times 4'$) with major axis parallel to the galactic plane and centered about $50''$ (≈ 2 pc) west of Sgr A*. The shell appears in expansion, compressing the cloud and probably creating the string of 4 HII regions at the border with M-0.02-0.07 and the

OH masers also observed around the shell. A life time of $5\ 10^4$ - 10^5 yr and a total explosion energy of $4\ 10^{52}$ ergs were derived from the source radio brightness and expansion velocity. 40 nearly simultaneous SN are needed to account for this energy and other scenarios have been proposed to explain Sgr A East energetics, including the explosive tidal disruption of a 1 M$_\odot$ star by the central massive black hole. Between $1.7-7$ pc ($40''$-$175''$) from the center lies the CND a clumsy, asymmetrical torus of neutral molecular gas and dust rotating (V$_R \approx 100$ km s^{-1}) around Sgr A West. The CND mass is 10^4 M$_\odot$, the gas temperature ≥ 100 K and it is observed in molecular transition lines (e.g. HCN) and also in infrared wavelengths, emitted by the dust heated by radiation coming from the central cavity. Its inner part has the shape of a ring whose edges bound the central cavity and the thermal source Sgr A West. The HII region Sgr A West was unambiguously separated by the non-thermal emission of Sgr A East in 1975, while the inner minispiral pattern was discovered in 1983 with the VLA. The bulk of the ionized gas (250 M$_\odot$) appears as extended emission of size 2.1 pc $\times$ 2.9 pc with average density n$_e \approx 10^3$ cm^{-3}, in which is embedded the denser *minispiral*, a 3 armed spiral structure (Fig. 3) orbiting around the GC, composed by northern and eastern arms, a central bar and a western arc. The radio spectrum resembles that of a typical optically thin HII region with T$_e \approx 6000$ K, emission measure $\approx 2\ 10^3$ pc cm^{-6} and ionization temperature T $\approx 3\ 10^4$ K. These parameters imply the presence of a ionizing source of UV luminosity L$_{UV} \approx 7.5\ 10^{37}$ erg s^{-1} and total flux of Lyman continum photons N$_{Lyc} \approx 1.2\ 10^{50}$ ph s^{-1}. Recombination emission lines allowed detailed kinematic studies of the gas, which show that Sgr A West is rotating from north-east to south-west and then towards north-west. This seems to imply that the western arc
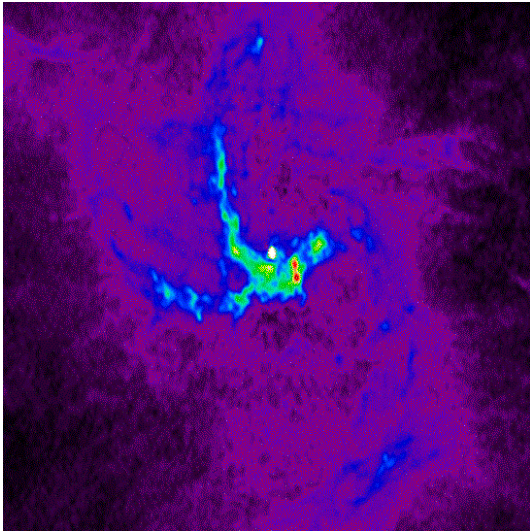
Figure 3. *Sgr A West minispiral observed with the VLA at 1.2 cm. The central white spot is Sgr A*.*

Figure 4. *Radio spectrum of Sgr A*. Minimum and maximum fluxes show the variability level.*

is the ionized edge of the CND, the N and E arms are tidally stretched streams of infalling gas and the bar is an extension of the N arm. Sgr A West is seen in front of Sgr A East and Sgr A East Core cloud but is behind the 20 km s^{-1} molecular cloud. Little north of the minispiral central bar and visible as a white point in Fig. 3 lies the compact source Sgr A* which must be seen in front of the minispiral bar even if embedded in the diffuse ionized cloud.

3. THE COMPACT RADIO SOURCE SGR A*

Sgr A* was discovered by Balick & Brown (1974), 3 years after Lynden-Bell & Rees (1971) had predicted that a compact synchrotron radio source should reveal the presence of a massive black hole (MBH) in the Galactic Nucleus. Sgr A* is indeed a compact, bright, non-thermal radio source, which coincides (within 50 mas) (Ghez et al. 2000) with the dynamical center of the Galaxy. The radio spectrum (Fig. 4) is an inverted power-law ($S_\nu \div \nu^\alpha$) with spectral index $\alpha \approx 0.33$ between 1 GHz and 800 GHz, and with low and high frequency cut-offs. Flux variability of 30-100%, around a value of $\approx$ 1 Jy, on timescales of few months is observed, and the average radio luminosity is estimated to $\approx$ 300 L$_\odot$. The source is also very static, an upper limit of 20 km s^{-1} has been set to its proper motion. Considering the high velocities of the stars of the region (500-1000 km s^{-1}) this unusual low value indicates that Sgr A* must be massive. A lower limit of 1000 M$_\odot$ to its mass was indeed derived, excluding the possibility of a stellar object. The apparent radio size of Sgr A* increases with wavelength as λ^2, which is the sign of source broadening due to ISM electron scattering. However at low enough λ (< 7 mm) the relation seems to flatten and the source is probably resolved by the VLBI. The most recent VLBI data at 1.4 mm provide a size of $\approx$ 0.1 mas (Krichbaum et al. 1998)
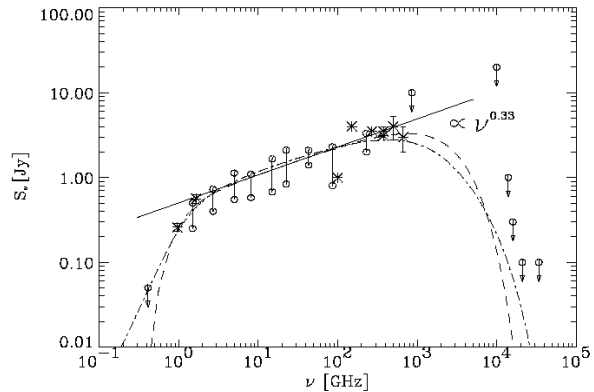
which at 8 kpc corresponds to only 1.2 10^{13} cm = 0.8 AU or, in terms of a 3 M$_\odot$ BH Schwarzschild radius (see § 6), of only $\approx$ 14 R$_S$. Moreover the source appears elongated with the intrinsic major axis $\approx$ 3 times greater than the minor axis and oriented in the North-South direction (Lo et al. 1998). This result, if confirmed, could indicate the presence of a weak radio-jet. Circular polarization is observed at several radio frequencies but until recently only upper limits ($<$ few %) were set for linear polarization. Aitken et al. (2000) have now discovered linear polarization at level of 10-20 % at sub-mm frequencies ($\geq$ 100 GHz). The sub-mm part of the Sgr A* spectrum seems peculiar also because it shows a bump of emission with respect to the extrapolation of the radio power-law. Indeed, using simultaneous observations at different frequencies from 10 cm to 1 mm, Falke et al. (1998) found at $>$ 100 GHz an excess which implies a change in the spectral slope.

4. EVIDENCES FOR A MASSIVE BLACK HOLE AT THE GC

High gas velocities in the vicinity of the putative MBH of the galaxy were also predicted by Lynden-Bell & Rees in 1971 as a consequence of the gravitational pull exerted by the BH. These authors suggested to search for radio recombination lines of the thermal gas close to the BH to measure gas velocities and then to estimate the BH mass. High velocities of the Sgr A West ionized gas have been indeed observed, since 1974, using the H recombination lines (H109α, H91α, H92α) the forbidden line λ12.8 μm of [NeII] and the λ2.17 μm Brγ line (Mezger et al. 1996; Yusef-Zadeh et al. 2000). These measures could show that the dynamics at radii R $>$ 1.5-2 pc (i.e. outside the CND inner ring) is dominated by the nearly-isothermal central star cluster, while within 1.5 pc from the center the dynamics is due to a central mass of $\approx$ 3 10^6 M$_\odot$ enclosed within $\approx$ 0.17 pc. However gas motion measures cannot constrain further the volume of the cen-

tral mass and also non-gravitational forces (magnetic fields, turbulence, etc.) may play a role making the interpretation of the recorded velocities not obvious. Star kinematic studies, based on both stellar dispersion and rotation velocities, started in 1978, with the aim of evaluating the central mass M(R) enclosed within the radius R down to distances < 0.1 pc. The most convincing results have been obtained in the last 8 years thank to high resolution NIR observations performed with speckle/adaptive optics in the K band (2.2μm), which allowed to provide independent determination of star velocities using measures of star proper motions. The recent paper by Genzel (2000) summarizes the results obtained both with the SHARP CCD camera mounted on the 3.5m ESO NTT telescope (Genzel et al. 1997) and with the NIRC camera at the 10 m Keck telescope (Ghez et al. 1998). About 1000 star with m(K) < 16 (= 0.25 mJy) were imaged between 1992-1999 within the central 1 pc ($25''$) with angular resolutions in the range 0.15-$0.05''$. Proper motions for 100 stars could be determined along with 200 high quality spectra. The important improvement provided by proper motion measures is that they allow measurements of stellar velocities of the very faint stars which are very close ($R < 0.6''$) to Sgr A* and which show motions at > 1000 km s^{-1} (1470 km s^{-1} for the closest star in projection, at $0.1'' = 800$ AU from the radio source). The simultaneous measure of proper motion and radial velocity for 32 stars between $1''$-$5''$ from Sgr A* also allowed to test the fundamental hypothesis of velocity isotropy assumed by most of the mass estimators. Combining radial and proper motions data and using various projected mass estimators Genzel et al. (2000) derived the mass distribution reported in Fig. 5. The enclosed mass for R > 1-2 pc can be accounted for by the isothermal star cluster (broken line in Fig. 5) but at lower radii, in particular to fit data at 0.015 pc (≈ 3000 AU), it is necessary either to assume a point mass of 2.9 10^6 M$_\odot$ (full line) or to invoke the presence of a dark cluster of objects with central density of 4 10^{12} M$_\odot$ pc^{-3} (dotted line). Even composed of stellar BHs, such a cluster would not be stable for more than 10^7 yr and the hypothesis of a massive black hole at the Galactic Nucleus is now extremely strong. The very recent discovery with the Keck of curvature in the trajectories of 3 of the closest stars to Sgr A* (Ghez et al. 2000), confirms that stars are orbiting around the GC, increases by a factor 10 the density required for an alternative dark cluster and proves that the radio source is at less than $0.05''$ from the dynamical center of the stars. NIR observations have also led to the discovery of a cluster of about 25 bright, young, hot stars most of them belonging to the complex IRS 16 centered $\approx 2''$ east of the GC. These very luminous stars show broadened and P-Cyg type HeI/HI emission lines which indicate that their helium rich surfaces are expanding as powerful stellar winds with velocities of V$_W \approx$ 500-1000 km s^{-1} and mass loss rates $\dot{M}_W \approx$ 1-80 10^{-5} M$_\odot$ yr^{-1} (Najarro et al. 1997). These outflows produce a hypersonic wind of density n$_W \approx 10^3$-10^4 cm^{-3} which pervades the central pc. These stars also emit $\approx 10^{38}$ erg s^{-1} in UV and
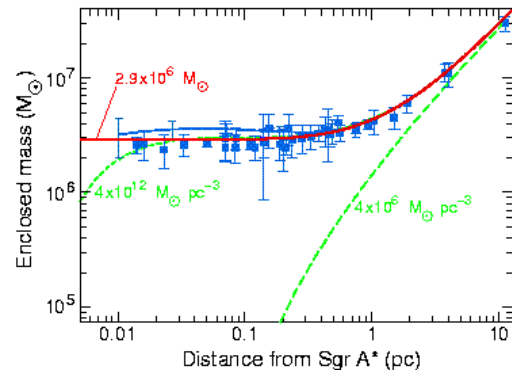

Figure 5. Enclosed mass vs. distance from GC.

can therefore totally account for the entire UV luminosity required to excite Sgr A West and to heat the dust of the central cavity and of the CND (§ 2). To conclude with IR observations we have to mention the important upper limits set by Menten et al. (1997) on the NIR flux from Sgr A* which imply an L$_{NIR} < 10^{35}$ erg s^{-1} for the compact radio source.

5. HIGH ENERGY OBSERVATIONS OF SGR A*

After the first detections of high energy emission from the general direction of the GC made with non-imaging instruments in the decade 1970-1980, the first real X-ray images with arcmin resolution were obtained with the Einstein Observatory (Watson et al. 1981). In addition to diffuse emission, 12 point sources were detected within the central $20'$, one of which, 1E 1742.5$-$2859, observed at $< 1'$ from Sgr A* with L$_{1-4\ keV} = 1.5\ 10^{35}$ erg s^{-1}. Between 1980-1990 several observations were carried out in the standard and hard X-ray bands and a number of transient sources were detected. The most remarkable observations were certainly those performed with the coded mask XRT instrument on SpaceLab2, which provided the first ever images ($3'$ resolution) of the GC in hard X-rays (3-30 keV) (Skinner et al. 1987). Sgr A* appeared again rather faint (L$_{3-30\ keV} = 5\ 10^{35}$ erg s^{-1}), in spite of the high expectations for an hard spectrum of the type of Cyg X-1. However in 1991 the Rosat telescope with $25''$ resolution in the band 0.1-2.5 keV, could separate 1E 1742.5$-$285 in 3 sources one of which, RXJ 1745.6$-$2900, was found within $10''$ from Sgr A* (Predehl & Truemper 1994). Rosat luminosity (L$_{0.8-2.5\ keV} = 3\ 10^{34}$ erg s^{-1}) however falls below 2 orders of magnitude from extrapolation of the N$_H$-corrected XRT luminosity. The possibility of strong variability or additional N$_H$ were considered but ASCA 1993-1994 observations in the range 0.1-10 keV, revealed presence of 2 point sources, a soft and stable one close to the Nucleus and another harder and transient about $1'$ away (Koyama et al. 1996). The authors concluded then that the flux observed by the hard X-ray instrument

on SL2 (also confirmed by ART-P/GRANAT, Pavlinsky et al. 1994) was due to the transient source and not to Sgr A*.

ASCA also confirmed and improved the results of EXOSAT, Tenma and Ginga on the presence of hard X-ray diffuse emission. A large part of the Nuclear Bulge seems permeated by hot plasma emitting X-ray diffuse emission with thermal spectrum of T ≈ 10 keV and numerous K emission lines of He-like and H-like ions. The diffuse source has an elliptical shape $1° \times 1.8°$ elongated on the galactic plane. The emission peaks around the center where a hot spot with an oval $2' \times 3'$ shape (= 4.8 pc $\times$ 7.2pc) and luminosity of $\approx 10^{36}$ erg s^{-1} was also imaged with ASCA. This emission is puzzling because at this temperatures the gas would not be bound by the GC gravitational potential. The estimated expansion of the large shell at sound speed provides an age of $\approx$ 50000 yr and input energy of $\approx 10^{54}$ erg for the gas, and continuous heating is required with power of $\approx 10^{41-42}$ erg s^{-1}. Tanaka et al. (2000) have recently argued against thermal origin of this emission and proposed that charge-exchange interaction of low-energy cosmic-rays with ISM contribute to it. ASCA also detected 6.4 keV neutral iron line diffuse emission in the Nuclear Bulge, and more precisely from Sgr B2 the most massive of the GMC. This fluoroscence line can be produced by high energy emission which is scattered in the neutral environment of a GMC. Murakami et al. (2000) estimated, comparing data to simulations, that an external source at a distance d, should have emitted about $L_{2-10\ keV} = 3\ 10^{39}$ (d/100 pc)^2 erg s^{-1} over 100 yr. This excludes binary transient sources but leaves open the possibility for a flare of Sgr A*. If emitted from Sgr A*, radiation should have been travelling through $\approx$ 300 l.y. to reach SGR B2. These data could then probe 300 yr ago flaring activity from Sgr A*. Similar conclusions were reached by Sunyaev & Churazov (1998) who investigated also dependence of the line characteristics and variability with position and time behavior of primary source, while Fromerth et al. (2001) found that data are also compatible with location of primary source inside the GCM.

To a be a faint source in X-rays does not prevent to be strong emitters in gamma rays, in particular for such extreme objects like BH, which are known to emit very hard radiation and suspected to generate e$^+$-e$^-$ annihilation line. The GC has been a priority target of the first satellite imager of soft γ-rays (30 keV - 1300 keV) SIGMA. SIGMA with its $13'$-$15'$ resolution and large field of view performed deep surveys of the galactic bulge between 1990-1997 cumulating nearly 10^7 s of data. SIGMA found that in this band the $1°$ region around the GC is dominated by the otherwise anodyne X-ray source 1E 1740.7-2942, which follow up observations revealed to be associated to radio-jets and which is now one of the 4 persistent galactic BH candidates X-ray sources. Sgr A* appeared instead silent. The only weak flare observed by SIGMA from the vicinity of the GC in 1991 (see Fig. 6), was attributed to a point source $> 9'$ away from

Sgr A* (Goldwurm et al. 1994; Vargas et al. 1996). A recent re-analysis of the whole SIGMA data by Goldoni et al. (1999) have provided the best low-energy γ-ray upper limits for this source (see also Fig. 7 and Goldwurm et al. 2000). The results imply $L_{30-300\ keV} < 1.2\ 10^{36}$ erg s^{-1}, and an upper limit (3 σ) of $3.3\ 10^{-4}$ ph cm^{-2} s^{-1} for narrow 511 keV line point source at the GC was also obtained with SIGMA (Malet et al. 1995). OSSE/GRO mapped the galactic diffuse 511 keV emission and could identify a bulge component of about the same value in flux than the above quoted SIGMA upper limit, with a positronium fraction of 0.89 (Purcell et al. 1997). Due to the limited angular resolution ($> 4°$), however it was not possible to estimate if any of this emission is from a central point source.

A source (2EG J1746-2852) in the Galactic Center was also detected by EGRET/GRO (Mayer-Hasselwander et al. 1998) at $>$ 30 MeV. The poor angular resolution of the instrument ($\sim 1°$) does not exclude it is actually diffuse. The spectrum is a broken power-law with photon indexes of 1.3 and 3.1 below and above 1900 MeV, which seems against pure π_0 decay origin, with total luminosity of $L_{>100 MeV} = 2.2\ 10^{37}$ erg s^{-1}. SAX (NFC/MEC) monitoring of GC has not provided new results on the Nucleus itself, however it was found that the soft component (T $\approx$ 0.6 keV) of the local diffuse emission seems related to Sgr A East and it is well interpreted as thermal emission from a SNR (Sidoli et al. 1999). The hard component (T $\approx$ 8 keV) instead lies along the plane as shown previously by ART-P and ASCA.

Chandra observations with the unprecedent angular resolution of 0.5$''$, carried out in fall 1999, have instead resolved the Rosat source in few components, one of which could be point-like and lies within 0.35$''$ from Sgr A* (Baganoff et al. 2001). The source, which may well be the real X-ray counterpart of the radio source, has a power-law spectrum rather steep ($\approx$ 2.7) and luminosity $L_{2-10\ keV} \approx 2\ 10^{33}$ erg s^{-1}. Althought the 0.5-2 keV flux is very uncertain due to the low accuracy of N_H estimation it seems clear that Sgr A* soft X-ray luminosity is well below the Rosat value.

6. THE PROBLEM OF SGR A* LOW-LUMINOSITY

In spite of the very compelling evidences for a MBH at the Galactic Nucleus, Sgr A* does not behave like a simple mass scaled-down AGN. Summing measured luminosities and considering the quoted upper limits, Sgr A* bolometric luminosity is

$$L_{Sgr\ A^*} < 5\ 10^{36}\ erg\ s^{-1}$$

The UV luminosity is uncertain due to the high extinction but the fact that Sgr A West ionization can be provided by the IRS 16 cluster of hot stars implies that there is not an additional strong source of UV, whose emission would also be re-emitted by the
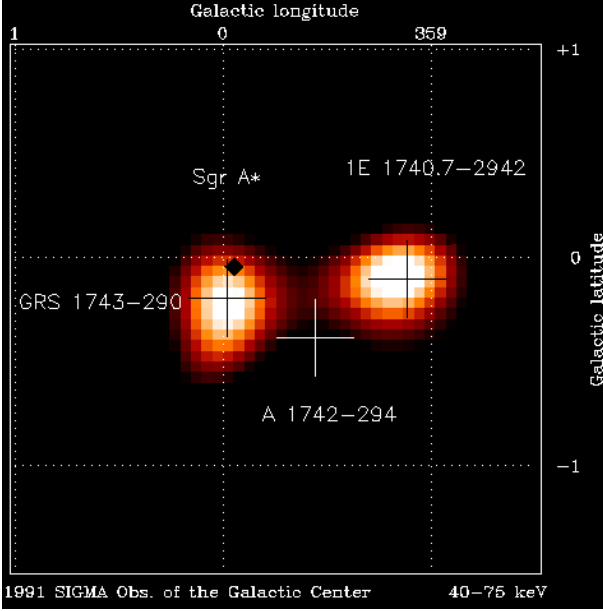
Figure 6. Image around Galactic Nucleus obtained by SIGMA in 1991. Black diamond is position of Sgr A*, and crosses of SIGMA sources of the region.

heated dust and observed in IR. The EGRET source can rise this value by a factor 5 but in any case the Nucleus remains sub-luminous.

For a BH at the GC with mass $M = 3.0 \, 10^6 \, M_\odot$, the Schwarzshild radius R_S and Eddington luminosity L_E are

$$R_S = \frac{2GM}{c^2} = 9.0 \, 10^{11} cm = 0.060 \; AU \sim 7.5 \; \mu as$$

$$L_E = \frac{4 \, GM m_p}{\sigma_T} = 3.9 \, 10^{44} \; erg \; s^{-1}$$

In spherical accretion, matter with density n_w flowing with relative velocity V_w within a distance R_A (accretion radius) from the BH is captured, undergoes a shock which dissipates the kinetic energy in thermal energy and then is accreted radially with free-fall velocity and mass accretion rate $\dot{M}_A$ providing a power L_A (accretion luminosity) given by

$$R_A = \frac{2GM}{V_w^2} = 1.6 \, 10^{17} \; cm = 0.05 \; pc \sim 1.3''$$

$$\dot{M}_A = R_A^2 \rho_w V_w = 5.5 \, 10^{22} \; g \; s^{-1} = 8.7 \, 10^{-4} \; M_\odot \; yr^{-1}$$

$$L_A = \frac{GM \dot{M}_A}{R_S} = 2.4 \, 10^{43} \; erg \; s^{-1} = 0.061 \; L_E$$

where wind parameters quoted in § 4 where used, i.e. $V_w = 700 \; km \; s^{-1}$, $n_w = 5.5 \, 10^3 \; cm^{-3}$. 3D simulations of the stellar winds from the IRS 16 cluster flowing into the GC black hole have been performed by Cocker and Melia (1997) using results of Najarro et al. (1997) and they obtained a mass accretion $\approx$ 1-2 times the value of $\dot{M}_A$. So the accretion luminosity is 10^6-10^7 times higher than the measured bolometric luminosity and efficiency of conversion of available energy in radiation must be lower than

10^{-6}. The final efficiency depends actually on how the matter, once captured at R_A is accreted, how reaches the BH event horizon, which are the characteristics of the flow and whether a disk forms. Cocker and Melia (1997) in their simulations also found that the accreted specific angular momentum l in units of cR_S ($\lambda = l/cR_S$) varies around an average of $\lambda = 40 \pm 10$ with the sign swapping on time-scales of ~ 100 years. This implies that the circularization radius $R_c \approx 2\lambda^2 R_S$ (distance at which angular momentum equals the Keplerian value) is < 3000 R_S and a large accretion disk probably does not form.

7. ACCRETION MODELS FOR THE GC BLACK HOLE

An optically thick and geometrically thin accretion disk has efficiency of the order of 0.1 and, if present around Sgr A*, would originate a bright spectral peak in the UV band similar to the blue bump of AGNs, followed by a steep Wien tail which may contribute little to X-rays. The low energy tail would extend to NIR and such component would violate the Menten et al. (1997) upper limits.

The first attempt to fit the entire spectrum of Sgr A* modeling the accretion into the massive BH was done by Melia (1992, 1994), who computed emission produced in pure spherical Bondi-Hoyle geometry. Without the viscous dissipation which occurs in disks, matter would fall into the hole heated up by simple adiabatic compression, and efficiency of conversion of gravitational energy in radiation would be very small. However it is usually assumed that matter carries, in the fall, the magnetic field, maintained in equipartition with the gas, and magnetic dissipation by turbulence or field lines reconnection can heat efficiently the particles which then emit synchrotron, free-free and inverse Compton radiation. With this model Melia (1992) could fit the available data for a black hole mass of $10^6 \, M_\odot$, a value smaller than recent estimates. In its 1994 model, Melia also included an optically thick disk at small radii, to account for the effects of the accreted angular momentum, but the Menten et al. (1997) IR upper limits are not compatible even with such small disk. Recently, Cocker and Melia (2000) revisited the model improving computation of the emitted spectrum and assuming magnetic field B in sub-equipartition by letting its value to be free parameter. Considering variability the model luminosities seem marginally compatible with the data and imply that B, which is of few mG at R_A ($\sim 10^5 \; R_S$), does not reach the equipartition value at intermediate radii. Only in the inner region of $\approx$ 5-25 R_S, where gas circularizes and a small Keplerian disk is formed, the magnetic dynamo can rise the field to values of the order of 200 G. The emission from this inner region could then account for the sub-mm excess and for its polarization. However this variant of the model fits the data only for an effective accretion rate < $10^{-4} \; \dot{M}_A$.

In 1995, Narayan et al. proposed that accretion flows for sub-Eddington rates ($\dot{M} < \dot{M}_E$) in systems

with BHs be dominated by advection. These models (ADAF) assume a very weak coupling between protons and electrons in the flow and the energy carried by protons is not transmitted efficiently to the radiating electrons but rather advected into the hole.

The plasma gets very hot (optically thin), flows with 2 temperatures ($kT_p \approx 10^9$ K, $kT_e \approx 10^7$ K), with nearly spherical geometry (geometrically thick disks), but with viscous dissipation and momentum transport. The radio spectrum is generated by optically thick self-absorbed synchrotron emission from hot nearly-relativistic thermal electrons at different temperatures. Each disk ring at radius R gives rise to a spectrum peaked at the critical frequency above which radiation becomes optically thin. A total flat spectrum is then produced by the superposition of these ring spectra. Highest radio frequencies are generated by the hottest electrons of the inner regions close to the BH while inverse Compton produces a weak tail in IR, optical and UV, and X-rays are produced by thin thermal bremsstrahlung from electrons at all radii till R_A. The best ADAF model for Sgr A* (Narayan et al. 1998) fits the radio data, the Rosat X-ray flux and the IR and hard X-rays upper limits (see Fig. 7) for the correct BH mass but for an accretion rate $\dot{M} \approx 10^{-5}$ $M_\odot$ yr^{-1}. This is more than a factor 10 lower than estimated from the IRS 16 stellar winds. Since in ADAF L $\div$ $\dot{M}^2$ the luminosity for 10 times the rate would be 100 times greater and the discrepancy is not easily explained (Quataert et al. 1999). To account for the EGRET γ-ray source Narayan et al. (1998) computed the contribution of decay of pions produced by proton-proton collisions in the very hot inner region of the ADAF. The spectrum could reproduce the EGRET spectral shape but not the flux normalization. On the other hands electrons produced by the muons seem able to naturally account for the *cm* part of the spectrum not well explained by the thermal electrons (Mahadevan 1998).

The spectrum of Narayan et al. 1998 fitted the Rosat flux and the new value of X-ray luminosity obtained with Chandra certainly makes more acute the problem of accretion rate (see Fig. 7). Blandford & Begelman (1999) argued that ADAFs must have outflows in form of winds and, more recently, it was also found that convection in the disk may reduce outward transport of angular momentum reducing the net flow of matter into the hole (Quataert & Gruzinov 2000). Both these new variants of ADAF (known as ADIOS and CDAF) could reduce effective mass accretion. However Quataert & Narayan (1999) discussed the spectral shape of ADAF with winds and found that since soft X-rays are produce far from the hole (between 10^4-10^5 R$_S$), outflows, expected in the inner regions, will not reduce the expected X-ray emission and discrepancy with the accretion rates is not resolved. Moreover the Chandra steep spectrum does not seem compatible with thermal bremsstrahlung. Another important difficulty for ADAF models is the recent discovery of linear polarization in the sub-mm band. In both ADAF and Bondi-Hoyle models this excess is produced in the inner regions of the flow and therefore even if radiation can be initially polarized, the accreting plasma encountered on the way out would depolarize the emission by Faraday effect (Agol 2000), unless very peculiar geometries are invoked. Observed values of polarization seem to imply accretion rates as low as 10^{-8} $M_\odot$ yr^{-1} making of course need for low-efficiency models much less important.

All these factors certainly revive the non-thermal models of Sgr A*. The flat (index ≈ 0.3) radio spectrum could indeed be interpreted as due to thin synchrotron radiation from a quasi mono-energetic distribution of electrons, e.g. accelerated by shocks inside the accretion flow. The low frequency cut-off is due to self absorption while the high frequency one to the cut off in the truncated power-law electron distribution. Such model was investigate by Beckert et al. (1996) and refined by Beckert & Duschl (1997). X-rays can then be produced by self synchrotron Compton (SSC) emission. The main difficulty was to correctly account for the X-ray flux and to explain the "ad-hoc" cut off in the electron distribution. Another non-thermal model for Sgr A* is the jet/nozzle model, recently re-discussed by Falcke & Markoff (2000) (see references therein). The authors propose that radio emission is generated in a compact radio jet, similar to those seen in AGNs, but less powerful. This model could explain the possible asymmetry in the radio and sub-mm shape of the source (Lo et al. 1998) which, if confirmed, would indeed favor the presence of a jet. The base of the jet where the acceleration of the magnetized plasma takes place, the nozzle, is a compact region where the sub-mm radiation is originated. The nozzle is close to the BH and to the inner part of the accretion flow. The jet mechanism is not known but the authors invoke a coupling between jet and accretion disk. As for the mono-energetic electron model the X-rays are produced by SSC and the expected spectrum seems to fit well the recent Chandra results. However the accretion flow must not provide relevant X-ray emission and the problems of low-efficiency accretion or of a much lower effective accretion rate than the one estimated from data on stellar winds remain.

Finally, the Sgr B2 6.4 keV line could indicate that Sgr A* is flaring, may be cyclically like the X-ray Novae. However if the accreted material is stored between the flares, in a large low-viscosity disk, the latter should be visible in IR.

8. PERSPECTIVES AND CONCLUSIONS

ADAFs have become popular in recent yeas because they seemed able to explain, in the frame of BH accretion disk thermal models, the low efficiencies observed in the nucleus of our Galaxy and of other close normal galaxies. However these models are now encountering serious difficulties, and non-thermal models become again competitive. All models however fail to explain why the closest known massive black hole to us radiates so little, unless we admit that it does not accrete the available matter as expected. Major advances in understanding of the physics of
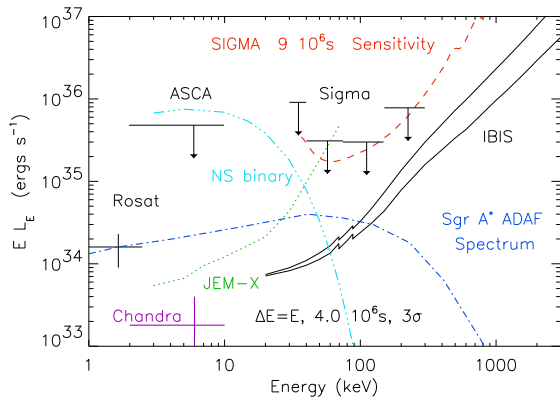
Figure 7. *IBIS (full lines) and JEM-X (dotted) INTEGRAL sensitivities and the ADAF spectrum (broken-dotted) of Sgr A* with SIGMA and ASCA upper limits, and Rosat and Chandra luminosities.*

the Galactic Center will be provided in the next years by new and more accurate observations, in particular at high energies. The Chandra and XMM-Newton observatories will probably address the question of the X-ray (0.1-15 keV) luminosity, variability and spectrum of Sgr A* and of the characteristics and origin of the local X-ray diffuse emission. The next ESA γ-ray (3 keV - 10 MeV) mission INTEGRAL will allow to study, if present, the ADAF hard X-ray component predicted by Narayan et al. (1998). Fig. 7 reports the expected sensitivity of the medium energy (20 keV - 10 MeV) instrument (IBIS) on-board INTEGRAL compared with the ADAF model. Detailed simulations (Goldwurm et al. 2000) show that IBIS will be able to detect the expected thermal bremsstrahlung hard component of Sgr A* in $4\ 10^6$ s. With INTEGRAL it will be possible to search for a compact source of 511 keV line at the GC. In spite most models do not predict a strong e^--e^+ annihilation line contribution from the MBH itself, Fatuzzo et al. (2000) argued that part of the 511 keV bulge component may be due to cumulative effect of pair production in the expanding shells of repeated Sgr A East type events. High energy observations with GLAST at > 100 MeV will resolve the standing problem of the EGRET source, possibly linked to the Sgr A* or to the non-thermal Sgr A East shell. The latter is also expected to provide detectable flux in the TeV range, making the GC an interesting target also for next generation of ground VHE/UHE γ-ray and neutrino experiments. Moreover the Galactic Center has been recognized as possible site of large cold dark matter concentration and annihilation (Gondolo & Silk 1999).

Sgr A* is probably the closest massive black hole, and in spite presently in low state of activity, remains a highly privileged target for astronomical multi-λ observations and for future astroparticle experiments.

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