An overview of the high-energy emission from the Galactic Center

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Abstract. The Galactic Center is a prominent source in X-rays and gamma-rays and the study of its high-energy emission is crucial in understanding the physical phenomena taking place in its dense and extreme environment, phenomena that are possibly common to other galactic nuclei. However this emission is also very complex and consists of both thermal and non-thermal radiation produced by compact and extended sources, surrounded by more diffuse components. In spite of the fundamental advances obtained in the last ten years with Chandra, XMM-Newton, INTEGRAL, HESS and Suzaku several questions remain open to investigations. I will review here the main results and the open issues on the high-energy diagnostic of the galactic nuclear activity.

1. Introduction

The Galactic Center (GC), the sky region of $\sim 4^\circ \times 2^\circ$ in galactic longitude and latitude respectively, surrounding the center of our Galaxy, and corresponding to about 600 pc $\times$ 300 pc size at the estimated distance of 8 kpc, has been observed with high-energy instruments since the very beginning of the X/gamma-ray astronomy. One of the major motivations of these surveys has been to measure the energetic radiation from the GC super-massive black hole (SMBH) that is now firmly detected (with an estimated mass of $4 \times 10^6 M_\odot$) and associated to the compact radio source Sgr A*. However several other interesting and in fact much brighter sources populate the region: variable X-ray binaries (XRB), supernova remnants (SNR) that interact with dense molecular clouds (MC), stellar clusters of young stars creating HII regions and emitting powerful stellar winds, non-thermal filaments, pulsar wind nebulae and a hot gas mixed with energetic particles. Totally obscured in the optical and ultraviolet wavelengths by the galactic plane dust, the GC is mainly observed from radio to infrared (IR) frequencies and then at high energies ($> 1$ keV). A radio picture of the region, that shows its complexity, is reported in Fig. 1 and general reviews are given by Mezger et al. 1996; Morris & Serabyn 1996; Melia & Falcke 2001; Melia 2007.

The high-energy data are particularly interesting to trace the most violent phenomena generated by strong gravitational or magnetic fields, and that give rise to particle acceleration and non-thermal radiation. In the recent years, with the launch of Chandra, XMM-Newton, INTEGRAL and Suzaku X-ray/gamma-ray observatories and with the operation of ground-based very-high-energy (VHE) gamma-ray observatories like HESS, this quest has led to some fundamental discoveries. I will summarise here these results, focussing on items other than Sgr A* emission, and updating my previous review works.
on similar subject (Goldwurm 2006, 2007, 2009) by reporting the most recent findings and discussing the still open questions.

2. Early X-ray and gamma-ray observations

The detection of high-energy emission from the GC dates back to the very beginning of the X-ray astronomy, in the 1960s, with devices mounted on sounding rockets. The first claim of detection of a galactic center X-ray source in Sagittarius appeared in a paper by Bowyer et al. (1965) of the Naval Research laboratory (NRL), reporting results from an Aerobee rocket flight in 1964. Several other measurements followed by the AS&E, MIT, Lockheed and again the NRL X-ray astronomy groups (Clark et al. 1965; Fisher et al. 1966; Gursky et al. 1967; Bradt et al. 1968). From these first investigations appeared that most of the newly discovered X-ray sources were clustering around the GC but the nucleus itself did not seem bright. In the 70s the region was monitored by the first X-ray satellites, Uhuru, Ariel 5 and HEAO 1 and other rocket experiments. The GC X-ray source (4U 1743-29) detected by Uhuru in 1970 appeared somewhat extended and either due to diffuse emission or to a composition of several sources (Kellogg et al. 1971) while Ariel 5 and other experiments revealed the presence of bright variable or transient objects (e.g. A 1742-294 and A 1742-289) and of several burst sources that were positioned with large error boxes. At the eve of the launch of the Einstein Observatory it was already clear (Proctor et al. 1978; Cruddace et al. 1978) that, in spite of the large activity of the GC region, the X-ray luminosity of the nucleus was much lower (< few $10^{36}$ erg s$^{-1}$) than in Active Galactic Nuclei (AGN).

The first GC X-ray images with arcminute resolution were however obtained only when, at the end of the 70s with Einstein (HEAO 2), it was possible to implement focusing mirrors for soft X-ray telescopes. Watson et al. (1981) showed then that the central 20' of the Galaxy at < 4 keV were dominated by diffuse emission with several weak point-like sources, one of which associated to Sgr A West and therefore including Sgr A*. This object was then resolved in 3 weaker sources with Rosat (Predehl & Truemper 1994) more then 10 years later leading to a measurement of soft X-ray luminosity of only $10^{34}$ erg s$^{-1}$ for the source coincident (within 10'') with the nucleus. On the other hand the GC SMBH could still shine in hard X-rays or even at 511 keV, the positron-electron annihilation line, since important, variable, fluxes were observed from the general direction of the GC since the late 60s at these energies. After all, BH binaries, like Cyg X-1, often emit the bulk of their accretion luminosity at > 100 keV. Hard X-ray observations of the GC started nearly as early as X-ray observations using NaI detectors on stratospheric balloons and led to significant detections of both hard (30-150 keV) continuum and 500 keV line from the GC (Haymes et al. 1969, 1975) with localisation uncertainties of few degrees. Further measurements confirmed in particular the presence of a GC 511 keV narrow and variable emission line associated to an orthopositronium continuum (e.g. Lingenfelter & Ramaty 1989).

Until the 90s however it was not possible, due to the uncertainties in these measurements, to disentangle the different components and these detections were still quoted as evidences for the presence of a massive BH at
the galactic center (see e.g Genzel & Townes 1987). Coded mask imaging technics operated a similar revolution in the hard X-ray and soft gamma-ray band as the one operated by the grazing incidence X-ray mirrors in the soft X-ray regime, by increasing angular resolution of hard-X/soft-gamma-ray telescopes to better than 30 arcmin. Observations in hard X-rays (3-30 keV) with coded mask telescopes XRT/SpaceLab2 (Skinner et al. 1987) and ART-P/GRANAT (Pavlinsky et al. 1994) and then in soft gamma-rays (30-1000 keV) with SIGMA/GRANAT (Goldwurm et al. 1994; Goldwurm 2001) showed then that the GC hard emission was rather due to the powerful hard XRBs of the region than to the nucleus. In particular 1E 1740.7–2942, one of the unpeculiar sources discovered with Einstein at about 40′ from Sgr A∗, was seen to fully dominate the images in those energy bands and was later recognized to be a very special object, the first BH microquasar. In addition, the SIGMA telescope set upper limits on the presence of a point-like source of 511 keV line (Malet et al. 1995) while in those same years OSSE/CGRO showed that the bulk of the 511 keV line emission was not variable but rather constant, diffuse and extended over the whole galactic bulge (Purcell et al. 1997) and therefore not directly related to Sgr A∗. At higher energies (> 100 MeV), where coded mask are not efficient, the EGRET/CGRO telescope detected a GC gamma-ray source sticking out from the general gamma-ray emission produced by cosmic-ray interaction with the dense gas of the region (Mayer-Hasselwander et al. 1998). This source was positioned slightly away from the nucleus (∼ 0.2°) but it could still be linked to Sgr A* given the large localisation error (Hartman et al. 1999).

Meanwhile a number of important results were also obtained on the GC X-ray diffuse emission. The japanese satellite GINGA discovered a prominent 6.7 keV iron line diffuse emission from the region (Koyama et al. 1989). The associated continuum component resembled to the diffuse galactic ridge emission (GRXE), distributed along the galactic plane and characterised by a thin hot thermal plasma spectrum, discovered in the early 80s with HEAO 1 and EXOSAT missions (Warwick et al. 1983). In the early 90s the ART-P telescope discovered a harder (> 10 keV) component associated to the molecular clouds of the region and this prompted the speculation that this emission could be due to reflection of X-rays emitted in the past by some very bright source, possibly Sgr A* itself (Sunyaev et al. 1993). The authors also pointed out that in this case a 6.4 keV line associated to the clouds shall also be detected. When the ASCA satellite in 1994 separated the diffuse contribution of the 6.7 keV line of ionized iron from the 6.4 keV one of neutral Fe atoms and showed that their distributions were different, with the 6.4 keV line one correlated to the molecular material, the hypothesis of a past flare from Sgr A* illuminating the clouds was then explicitly formulated (Koyama et al. 1996).

At the turn of the century, a new era of high-energy astronomy has been opened with the launch of the Chandra, XMM-Newton (1999) and Suzaku (2005) X-ray observatories; with the launch of the gamma-ray missions INTEGRAL (2002) and FERMI (2008) and the start of operations of VHE gamma-ray ground telescopes like HESS (2003).
Figure 1. Radio image of the galactic center at 90 cm from VLA data, on a grid of galactic coordinates spaced by 0.5° and compared to hard X-ray contours in the 20-40 keV band from the 2003-2004 INTEGRAL observations (Belanger et al. 2006).

Figure 2. X-ray image of the galactic center obtained with the deep survey of the Chandra observatory in the 1–8 keV range (for the color figure: red is for 1–3 keV, green for 3–5 keV and blue for 5–8 keV) (Muno et al. 2009).

3. The Galactic Center in the X-ray band

In the 1-10 keV X-ray band the GC is dominated by few bright, sometimes transient, X-ray binaries (e.g. 1E 1740.7–2942 or 1E 1743.1–2843). The region also contains a large population of weak point-like persistent and transient sources, several components of diffuse emission, several peculiar sources of thermal and non-thermal radiation and finally a weak central emission associate to Sgr A∗ (Fig. 2).
3.1. The inner 3 pc: Sgr A* and its close environment

Thanks to the exceptional resolution of the Chandra Observatory (∼ 0.5″) it has been possible to map in detail the central arcminute (2.4 pc) of the galaxy in X-rays (Fig. 3 left). As for the whole GC, the X-ray morphology is quite different from the radio one, which is dominated here by the characteristic minispiral of Sgr A West, and from the IR one, dominated by the hot stars and by the dust associated to the minispiral or the circumnuclear disk. Several weak discrete X-ray sources were detected, surrounded by a diffuse emission (Baganoff et al. 2003).

In the very center Chandra resolved the central Rosat source in several components and detected at the position of Sgr A* a very weak source with a steady 2-10 keV luminosity of only 2 × 10^{33} erg s^{-1} (compared to the Eddington luminosity of ∼ 5 × 10^{44} erg s^{-1} for the 4 × 10^6 M_☉ SMBH), a steep spectrum and somehow extended over about 1″ (Baganoff et al. 2003). The quiescent Sgr A* emission is so low that it even challenges the radiative inefficient accretion flow models (RIAF) (Narayan et al. 1995, Yuan 2010) developed to explain the low luminosity of the galactic nucleus and in general the behavior of black holes in low accretion rate regime. The steep spectrum seems also little compatible with the hard thermal bremsstrahlung of such models, although the apparent extension of the source appears consistent with an emission that starts at the Bondi radius (∼ 10^5 R_S, where R_S is the SMBH Schwarzschild radius ∼ 1.2 ⋅ 10^{12} cm or 1″ at the GC) as predicted by such theories.

The surrounding diffuse emission (within 15″ radius) has similar spectrum and likewise shows an iron line centered at 6.55 keV, which indicates fluorescence from plasma in non equilibrium ionization (NEI) (Xu et al. 2006). This hot NEI plasma just around Sgr A* has been explained as due to the interaction of the powerful stellar winds generated by the massive stars of the nearby young star clusters (Rockefeller et al. 2004; Quataert 2004), stellar winds that shall also provide the bulk of the material accreting in the supermassive black hole. A cometary source (G359.95-0.04) at about 10″ from Sgr A* was also detected and interpreted as a pulsar wind nebula confined by ram pressure. In spite of its very weak X-ray emission it has been proposed (Wang et al. 2006) as candidate for the counterpart of the bright central TeV emission (sect. 4). The closeby IRS13 star cluster bright in infrared and supposed to host an intermediate-mass black hole, was also identified as another weak discrete object of the central parsec.

3.2. Flaring activity of Sgr A*

One of the major results of the Chandra monitoring of the GC has been the discovery of X-ray flares from Sgr A* one year after the detection of the quiescent emission (Baganoff et al. 2001). Follow up monitoring both with Chandra and XMM-Newton have, since then, led to detection of several such events (Goldwurm et al. 2003; Bélanger et al. 2005; Porquet et al. 2003, 2008; Trap et al. 2010, 2010b). These flares typically occur randomly once a day, last 1 to 3 hours, and show a flux increase by factors up to 160 times the quiescent value, with the most bright ones reaching luminosities of ∼ 3 × 10^{35} erg s^{-1}. The spectra do not seem to vary during the event and usually display a harder spectral slope than the quiescent emission even if the brightest ones (and the most precisely measured) appear softer. The flare duration and the observed short-time-scale variations, some of them as short as to 200 s, indicate that the X-ray emission
is produced within 20 R_\odot. These flares allow us then to explore the inner region of the accretion flow and have been investigated deeply since their discovery. They cannot be accounted for by the standard RIAF models, for which the X-ray emission is produced from the whole accretion flow starting at the accretion radius, and clearly a variable, non-thermal component plays a major role during the flaring states. Whether this component is generated in a small hot accretion disk (Liu et al. 2004), at the base of a compact jet (Markoff et al. 2001) or in the inner region of a RIAF accretion flow (Yuan et al. 2004) is still matter of debate (Yuan et al. 2010). Most of these models can account for the observed flare X-ray spectral shapes, but they predict different correlations between fluxes at different frequencies.

For these reasons, and after the discovery in 2003 of near-infrared (NIR) flares from Sgr A* (Genzel et al. 2003; Ghez et al. 2004), large efforts have been devoted in the recent years to carry out large multiwavelength (MWL) campaigns (from radio to gamma-rays) on Sgr A* (Eckart et al. 2004, 2006, Yusef-Zadeh et al. 2006, 2009, Hornstein et al. 2007, Marrone et al. 2008, Dodds-Eden et al. 2009). While NIR emission in Sgr A* flares is nearly certainly produced by synchrotron emission, it is still not clear whether X-rays are originated by inverse Compton (IC) or synchrotron mechanism as several recent results have shown that IC may imply extreme parameters for the emitting region (Dodds-Eden et al. 2009; Trap et al. 2010). Moreover delays of radio and sub-mm flares with respect to NIR or X-ray events have been interpreted as due adiabatic expansion of the emitting plasma (Yusef-Zadeh et al. 2006b). The large MWL campaigns are therefore now devoted also to test the expansion paradigm and set constraints on such process (Trap et al. 2010b).

Another essential, but also somehow controversial result on Sgr A* flares is the possible presence of quasi-periodic modulation on timescales of about 20 minutes, which, if confirmed, would favor disk over jet models for Sgr A*.

Initially observed in the NIR data (Genzel et al. 2003) this feature was then reported also in X-ray flares (Aschenbach et al. 2004; Béclanger et al. 2006b). If
such a modulation is real and is associated to orbital motion at the last stable orbit of the accretion disk, then the observed timescale implies that the SMBH is rotating with a spin parameter of $\sim 0.2$ or higher. However several recent studies do not confirm the previously detected QPO signals in IR (Meyer et al. 2008; Do et al. 2009) and X-ray (Belanger et al. 2006) light-curves when red-noise and all other effects are properly considered. In spite of other NIR hints of modulation both in flux and in linear polarization (Eckart et al. 2006b, Dodds-Eden et al. 2009) the matter is not settled and investigations are in progress. For what concern the X-ray data, all recent observations of X-ray flares, including those in 2007 and 2009 with XMM, do not show quasi-periodic modulation in the light curves.

3.3. The inner 20 pc: Sgr A East

Moving from Sgr A* outwards, the morphology of the X-ray emission clearly shows an asymmetry towards positive galactic longitudes, with a bright diffuse oval source associated to the radio source Sgr A East (Fig. 3 right). The detailed analysis of this emission with Chandra and XMM has clarified the nature of Sgr A East, which appears now to be a single, compact, mixed-morphology SNR, where the non-thermal radio shell surrounds a centrally peaked thermal X-ray emission (Maeda et al. 2002). The X-ray plasma has 2 components, one at 1 keV and the other at 4 keV (Sakano et al. 2004). High element abundances ($Z \sim 4$) in the center of the source indicate that part of the emission is due to heated SN ejecta. The X-ray data show now that Sgr A East, apart from its high plasma temperature and the dense medium where it expands, is not an exceptional SNR, nor the result of several SN explosions or of the explosive disruption of a star by the SMBH as speculated previously. It rather appears to be the product of a typical SN II or a SN Ia occurred about $10^4$ yr ago or less. The most recent investigations with Chandra (Park et al. 2005) and Suzaku (Koyama et al. 2007) have basically confirmed all this, with a supporting evidence for a SN II origin and also the detection of an additional power-law component. This non-thermal emission could be due either to the cumulated contribution of the point source population detected with Chandra (see below) or to a genuine non-thermal X-ray emission generated by the SNR. Some authors have speculated that the Sgr A East shell of swept up interstellar matter could have reached the SMBH feeding it and triggering the Sgr A* outburst of hard emission that is now illuminating Sgr B2 (Maeda et al. 2002). However the role of Sgr A East in feeding the black hole with swept up material have been questioned in favour of a picture where a GC past X-ray outburst was rather generated by the interaction of the SNR shell with dense material of the 50 km/s molecular cloud (Fryer et al. 2003).

3.4. The X-ray discrete source population

The Chandra monitoring of the GC with a total exposure of 2.25 Ms led to the detection of over 9000 discrete sources in the $2^\circ \times 0.8^\circ$ region around the nucleus (Muno et al. 2009). These sources appear spatially distributed as the stellar population, which is dominated by old stars of the inner galactic bulge, but with density enhancements correspondent to the 3 young star clusters of the region, the Arches, the Quintuplet and the Galactic Center clusters. While in these
star forming regions young high-mass X-ray binaries, pulsars, or Wolf-Rayet/O stars in colliding-wind binaries may contribute significantly to the population, the bulk of the weak sources, with luminosities between $10^{31}$-$10^{33}$ erg s$^{-1}$, are probably cataclysmic variables (CV) with a good fraction made of the hard magnetically-accreting white dwarfs.

The brightest sources, with luminosities larger than $10^{34}$ erg s$^{-1}$ are mostly low mass X-ray binaries, like the persistent sources 1E 1740.7–2942 and 1E 1743.1–2843, some are transients and some display type I bursts indicating that the compact object is a neutron star (e.g. GRS 1741.9-2853, see Trap et al. 2009). A total of 19 such XRBs have been detected in the GC region since the beginning of X-ray astronomy with 8 of them discovered by Chandra, XMM or Swift in the last 10 years (Muno et al. 2009). More than 20 diffuse non-thermal features, identified in the central 40 pc and not associated with known objects, have been interpreted as PWN (Muno et al. 2008). These objects may provide important contribution to the gamma-ray emission as we know that they are sites of particle acceleration. The peculiar PWN G09+01 that is also a shell SNR and a prominent extended object in X-rays is indeed the second brightest source of the region at TeV energies (Aharonian et al. 2006).

3.5. The hot component of the X-ray diffuse emission

The diffuse X-ray emission of the galactic center region is complex and still under intense investigation but it certainly consists of at least three components (Muno et al. 2004, Park et al. 2004, Koyama et al. 2009): a patchy soft emission well described by a low temperature ($\sim$1 keV) plasma model, a more uniform 6.7 keV line associated to a continuum emission described by a hot (kT $\sim$ 7 keV) plasma, and a clumpy 6.4 keV iron line component well correlated to molecular material. The soft component, traced by low-energy ($<$ 3 keV) K$\alpha$ and K$\beta$ lines of He-like and H-like ions of Si, S, Ar, Ca, and in particular by the strong He-like K line of sulphur at 2.46 keV, can be fully explained by the interaction of supernova remnants or stellar winds from young and massive stars with the interstellar matter of the region. The estimated SN rate and the concentration of this component towards the star forming regions close to the radio arc and the Arches cluster are indeed consistent with these interpretations. The origin of the other components is more uncertain.

The hot component, characterised by the strong He-like (6.7 keV) and H-like (6.9 keV) ionized iron lines, is uniformly distributed, concentrated along the galactic plane with a peak towards the center and it is very similar to the GRXE. The interpretation of a diffuse hot plasma emission with temperature of 6-7 keV is problematic because such a hot gas cannot be confined in the region and it would escape in $< 10^3$ yr. Its regeneration would require a too large amount of energy and an unknown source of power. Some authors have proposed that the gas be dominated by helium rather than hydrogen, in which case it would be bound to the region (Belmont et al. 2003). The motion of molecular clouds through the strongly magnetized medium of the GC could then provide a heating mechanism, by dissipation of hydromagnetic waves energy. Another possible explanation is that the GC hot component is simply produced by an unresolved population of weak discrete sources, presumably CV (Wang et al. 2002). Revnivtsev et al. (2007, 2009) have indeed shown that this
is the case for the GRXE. These authors have analyzed a Chandra galactic ridge ultra-deep field and found that as much as 88% of the diffuse 6.7 keV emission is explained by discrete sources, mostly accreting white dwarf with 2-10 keV luminosity in the range $10^{31}$-$10^{32}$ erg s$^{-1}$ or coronally active binary stars with lower luminosities. A similar situation could hold for the GC, and this interpretation is supported by the similarity of the hot component spectrum with the cumulated spectra of the GC weak point sources observed with Chandra (Muno et al. 2004). The point-source population detected with Chandra can account only for a fraction of the total diffuse emission of the GC region, from 10-20% in the central area (Muno et al. 2004) to 40% in a region centered at negative longitudes (Revnivtsev et al. 2007). In order to explain the whole hot diffuse component the luminosity function of point sources would have to be extrapolated downward by few orders of magnitude. Moreover the spatial distribution of the diffuse component does not seem to be fully compatible with the smooth one expected from point sources (Muno et al. 2004).

Recent results obtained with Suzaku (Koyama et al. 2007, 2009), through a detailed spectral study of the diffuse emission lines of ionized iron and nickel, show that the line centroids, widths and flux ratios favor a collisional excitation plasma in ionization equilibrium with temperature of 6.5 keV. Suzaku measurements also show that the line emission is much less prominent along negative longitudes unlike the distribution of weak discrete sources. These facts seem to support again the hypothesis that the GC hot diffuse emission contains an important fraction of truly diffuse component but the issue is still highly debated.

### 3.6. The 6.4 keV line diffuse emission

The other distinct component of the GC X-ray diffuse emission is the 6.4 keV fluorescence line of neutral or weakly-ionized iron. This has a different morphology than the 6.7 keV line, being much less uniform, clumpy and clearly correlated to the molecular material of the Central Molecular Zone (CMZ). The fluorescence line at 6.4 keV ($\text{K}_\alpha$ of Fe) is produced by the emission of a photon that follows the extraction of an electron from the inner shell (K) of neutral iron atoms as the result of the electron transition from the second shell (L). Collisionally-ionized iron atoms in a hot plasma would rather produce lines in the 6.5-6.9 keV range, associated to a plasma continuum spectrum. Thus, the origin of the 6.4 keV line is certainly non-thermal and must be associated either to irradiation by photons with energies higher than 7.1 keV (Sunyaev & Churazov 1998) or interaction of energetic particles, most probably low energy electrons (Valinia et al. 2000). In the case of photoionization, a K edge absorption feature at energies higher than 7.1 keV is produced in the underline continuum. In both cases a continuum emission should be associated to the line: in the case photo-ionization it is due to the Thomson scattering of the incident radiation by the electrons of the cold material while in the case of interacting particles it is produced mainly by non-thermal bremsstrahlung of the energetic electrons. In case of irradiation and when the primary source is not contributing to the continuum the line should display a large equivalent width ($\sim 1$ keV). The main feature in the GC 6.4 keV images is Sgr B2, which is the densest (core densities of $10^5$-$10^6$ cm$^{-3}$) and most massive ($\sim 10^6 \text{ M}_\odot$) of the MC of the galaxy, and is located at about 100 pc in projection from the nucleus. Originally observed with ASCA...
(Koyama et al. 1996; Murakami et al. 2000) it was later explored with Chandra (Murakami et al. 2001) and recently with Suzaku (Koyama et al. 2009). The emission was interpreted as fluorescent line due to scattering of hard X-ray emission coming from an external source, possibly a strong outburst (∼10^{39} \text{ erg s}^{-1}) of hard X-rays from Sgr A* occurred some 300 yr ago that have traveled the distance to Sgr B2, illuminating the dense cloud and generating the Fe line and the reflected hard X-ray emission. Hard (> 10 keV) X-ray emission from Sgr B2 has been clearly observed up to 200 keV with INTEGRAL (Revnivtsev et al. 2004) supporting the model of an X-ray reflection nebula (sect. 4). These authors also demonstrated that the emission line intensity has been constant till about 2000 and therefore that the original outburst must have lasted at least 10 years, excluding an X-ray binary as possible primary source. The Fe Kα line has been detected in other molecular clouds of the CMZ, like Sgr C (Murakami et al. 2001b; Nakajima et al. 2009) and G0.1-0.1 (Yusef-Zadeh et al. 2002) but not in all and a correlation of certain 6.4 keV hot spots with non-thermal radio filaments, that indicate presence of accelerated electrons, has been found with Chandra (Yusef-Zadeh et al. 2007). These elements seem to favour the alternative interpretation for the 6.4 keV line origin, namely the iron excitation by subrelativistic particles, either electrons (Valinia et al. 2000; Yusef-Zadeh et al. 2002, 2007), or protons (Dogiel et al. 2009).

Although Suzaku with its high spectral resolution and low background level has provided more precise spectral measurements of the GC Fe Kα line (Koyama et al. 2009; Nakajima et al. 2009), the most convincing evidences that support the photon-ionisation model from an external source, come now from the recent detections of variability of the line and associated continuum, a signature predicted and modelled in detail by Sunyaev & Churazov (1998). First indication of local variability in the X-ray continuum (not in the line) of MC located between Sgr A* and G0.1-0.1 were reported using Chandra data (Muno et al. 2007). Then, using archival data of several satellites (ASCA, XMM, Chandra) and Suzaku measurements, it has been shown that Sgr B2 Fe Kα emission is changing as it would be produced by a wave front passing through the different components of the molecular complex (Koyama et al. 2008; Inui et al. 2009). But new extremely compelling evidences are given now by two crucial measurements. The first is the significant detection of time evolution of the hard X-ray emission from Sgr B2 observed over 7 years by the same instrument on the INTEGRAL satellite (Terrier et al. 2009, 2010). The decrease in the 20-60 keV flux of Sgr B2 is compatible with the reported decay of the 6.4 keV line intensity and best explained by a X-ray reflection nebula scenario where the fading of the reflection component is due to the propagation of the outburst decay through the molecular complex. Even more striking is the discovery of variations in the 6.4 keV line flux and morphology from the MC around 15' from Sgr A* between 2002 and 2009 obtained by Ponti et al. (2010) using the large XMM database of the GC. These authors report a significant decrease of G0.1-0.1 flux, an increase with apparent superluminal propagation of the emission along a molecular feature called ”bridge” and a constant behavior of other MC of the region. Such a variability and in particular the superluminal propagation exclude the particle model as particles cannot produce such rapid changes. On the other hand, for a X-ray nebula scenario, the constraints on the illuminating primary source indicate Sgr A* as the most probable candidate. Using a new
localisation of Sgr B2 along the line of sight and assuming a cloud distribution that is coherent with radio molecular line data these authors also show that the complex pattern of variations, including the decay in Sgr B2, can be due to one single outburst of Sgr A* that started 400 years back and ended about 100 years ago. The beginning of the burst is switching on the bridge, while its end has reached both Sgr B2 and G0.1-0.1. While the Sgr A* single outburst is not fully demonstrated by the data, these measurements clearly indicate that the galactic supermassif black hole has been bright, for few hundred years, with a luminosity of about $10^{-5}$ times its Eddington luminosity till about 100 years back. Thus Sgr A* was remarkably more similar to typical low-luminosity AGN in the recent past than it appears today.

4. The Galactic Center in gamma-rays

The GC emission at energies > 20 keV has been deeply explored in the last 10 years with INTEGRAL, HESS and more recently with FERMI. INTEGRAL has monitored the GC for more than 20 Ms between 2003 and 2009, obtaining with the IBIS/ISGRI telescope the most precise GC images ever collected in the 20-800 keV band (Belanger et al. 2006; Terrier et al. 2010) (Fig. 5). In this band the emission is dominated by bright and variable XRB with the hardest one being the BH microquasar 1E 1740.7-2942, but INTEGRAL also detected a faint and persistent emission coming from the very center of the Galaxy, compatible with a source located within 1' of the Sgr A* position. Due to the IBIS angular resolution ($\sim 13'$ FWHM) this source (IGR J17456–2901) cannot be identified...
with the SMBH or other objects of the dense central region. The lack of variability and of a bright discrete X-ray counterpart suggests that it is rather a diffuse emission concentrated in the inner central 10-20 pc (Béanger et al. 2006) or the sum of the contribution of unresolved point-like sources (1). The spectrum at $> 20$ keV cannot be explained by the extrapolation of the thermal plasma with $kT$ of 6.5 keV used to model the bulk of the X-ray diffuse emission and a non-thermal component extending up to 150 keV with steep spectral slope is clearly present and its origin is still unexplained. While the low-energy emission can be understood as the sum of unresolved weak discrete sources even the hard Intermediate Polars CV are not hard enough to explain the observed signal at $> 100$ keV. However the high-energy part of the spectrum ($> 50$ keV) could be be produced by closeby MC and this would explain the slight displacement observed in the centroid of IGR J17456–2901 at high energies. The presence of hard ($> 10$ keV) non-thermal emission from the GC was later confirmed with Suzaku (Yuasa et al. 2008) which also showed that it could be more extended than the central 20 pc. Simultaneous XMM-INTEGRAL observations performed during the 2007 bright Sgr A* X-ray flare, set upper limits on the variable component of the gamma-ray ($> 20$ keV) emission of IGR constraining somehow the Sgr A* flare mechanisms (Trap et al. 2010) and confirming that these flares do not contribute significantly to the central soft gamma-ray emission. In addition, INTEGRAL detected hard X-rays from Sgr B2 (IGR J17475-2822) (Revnivtsev et al. 2004), and especially, its significant decay between 2003 and 2009 (Terrier et al. 2009, 2010), fully compatible, as discussed in sect. 3.6, with the decay observed in the 6.4 keV line and with the hypothesis that Sgr B2 is a reflection nebula, scattering radiation generated by Sgr A* in the past.

Concerning the 511 keV line emission, the spectrometer on INTEGRAL has now mapped the sky with the highest accuracy available and has shown that this emission is extended over the galactic bulge ($\sim 8^\circ$ FWHM), is composed by both a bulge and a weaker disk components, and that the positron-electron annihilation take place partly in a warm neutral gas and partly in a warm ionized medium. The origin of the bulk of the positrons however is not yet understood (see Skinner et al. 2008 for a recent review). While the favorite mechanisms are not generally located in the very center of the Galaxy, a possible role of the SMBH in generating positrons has been investigated recently (Cheng et al. 2006; Totani et al. 2006).

In the VHE gamma-ray band the new generation of Atmospheric Cherenkov Detectors (ACD) have provided spectacular results on the GC. HESS, the most sensitive and precise of them, reported (after the first detections with Whipple and Cangaroo) the presence of a bright TeV point-like source centered within 1′ from Sgr A* (Aharonian et al. 2004, 2009). The source is constant and displays a power-law spectrum extending from 300 GeV up to $> 10$ TeV with a break around 15 TeV. It cannot be explained by heavy dark matter particle annihilation, because the spectrum is too hard and would imply too massive particles. It is rather attributed to interaction of accelerated leptons or hadrons, but the mechanism, site of acceleration and nature of primary particles are not yet identified. The expanding shell of the Sgr A East SNR, once considered as the best candidate for the TeV central source (Crocker et al. 2005), is it now formally excluded by the most recent HESS determinations of the location and error box of the source, which appear well centered on Sgr A* and too far from Sgr A East.
centroide (Acero et al. 2010). A serious candidate for HESS J1745–290 is instead the energetic cometary-like pulsar wind nebula (G359.95–0.04) (sect. 3.1) that could contribute to the TeV emission by IC scattering of the strong ambient radiation by the electrons accelerated in the nebula. Otherwise the SMBH is still a potential candidate (Aharonian & Neronov 2005) even if the GC HESS observations during a Sgr A* flare observed with Chandra have shown that the central TeV source did not vary during the eruption (Aharonian et al. 2008) and does not display variability on any time scale. Even if HESS J1745-290 is not directly connected to Sgr A* flares, particles accelerated in the inner regions close to the BH could propagate and interact with the surrounding matter close enough to produce a point-like source for the present ACD telescopes. The second brightest source of the region at TeV energies is the composite PWN and shell SNR G09+01 but the HESS collaboration has also reported the discovery of TeV diffuse emission closely correlated to the molecular clouds of the CMZ (Aharonian et al. 2006). The spectrum and distribution of this emission seem consistent with the idea that the central source (which has similar spectrum) accelerated in a recent past (few kilo-years) the hadrons that diffused in the region interacting with the molecular gas. Other studies (Wommer et al. 2008) seem to show that, in order to explain the smooth distribution of the emission, the origin of the hadrons cannot be the central source nor a distribution of point-like objects (e.g. pulsar wind nebulae). Those authors concluded that only a relativistic proton distribution accelerated throughout the intercloud medium can account for the TeV emission profile measured with HESS.

In the gamma-ray domain of medium-high energies the FERMI observatory, launched in June 2008 and working in the range 50 MeV - 100 GeV, has confirmed the EGRET results by detecting a source close to Sgr A*, listed in the FERMI/LAT catalogue (Abdo et al. 2010) as 1FGL J1745.6–2900c at a position compatible with several possible candidates including the SMBH, the PWN G359.95–0.04 and Sgr A East. No variability has been reported until now for this source. It is interesting to note that another significant excess (1FGL J1747.6–2820c) compatible in position with Sgr B2 is also listed in the FERMI catalogue while EGRET did not detect any excess emission in Sgr B2 (Mayer-Hasselwander et al. 1998). Obviously a specific, thorough analysis of FERMI data is needed in this complex and confused region of sky to measure the effective excess emission with respect to the one that is expected from cosmic ray (CR) interaction with the dense interstellar matter. Indeed the gamma-ray measurements can indicate whether the CR production and density in the GC is enhanced with respect to local or galactic disk values. Several measurements seem in fact to indicate that the ionization rate in the CMZ, with an estimated value of $3 \times 10^{-16}$ s$^{-1}$ for Sgr B2, is 10 times higher than in the galactic disk. However the additional CR component (factor 10) required by the GC TeV diffuse emission for the hadronic model has a hard spectrum, its gamma-ray contribution become negligible at $< 100$ GeV and cannot explain the additional ionization rate (Crocker et al. 2007) for which a specific steep low-energy component seems needed. To fit all these elements together, including a possible lack of detection of Sgr B2 in the GeV range and the lack of detection of non-thermal radio emission from the secondary leptons produced by the hadronic interactions (Crocker et al. 2007), more results are needed in particular in the FERMI energy band.
In conclusion: gamma-ray emission from the GC has now been clearly detected, however its origin and nature are not fully understood and several new questions arise. The data that are being collected will certainly provide new results in the near future and will possibly clarify some of the listed issues.

5. Open questions and perspectives

As discussed above, the topics related to the high-energy GC emission that are today still highly debated concern: the mechanisms of both quiescent and flaring emission of Sgr A*; the characteristics of its activity in the recent past; the origin of the diffuse 6.7 keV and associated continuum emission (sum of discrete sources or genuine diffuse hot component); the nature of the 6.4 keV diffuse emission and the associated non-thermal continuum; the nature of the Integral, Hess and Fermi sources detected in the very center of the Galaxy; the mechanism of production of the TeV and GeV diffuse emission and the origin and role of accelerated particles in the emission and ionization state of the region.

Future high-energy observations coupled to MWL campaigns will probably elucidate the mechanisms of Sgr A* flares in the coming years and address some of the main issues on Sgr A* physics. These programs will possibly settle the issue concerning the presence of periodicities in the Sgr A* emission during flares and will provide more thorough measurements of the broad band spectra of Sgr A* during these events up to 10 keV. Chandra, XMM and Suzaku will continue to monitor the properties and the variability of the diffuse X-ray emission, testing the reflection nebula paradigm and exploring the nature of the hot diffuse component. FERMI will provide soon important new results on the central GeV source and Sgr B2 while the next generation of ACD (e.g. HESS 2 and the Cherenkov Telescope Array) will map in the future the GC at TeV energies with increased precision. To finally solve the puzzle of the hard X-ray emission detected by INTEGRAL (and Suzaku) at the very center of the Galaxy and to fully understand the related items it will be however necessary to wait for focusing instruments of hard X-rays. With the stop of the Simbol-X mission ([Ferrando et al. 2008; Goldwurm 2008]), perspectives are less optimistic in this domain now. Nevertheless the data of Astro-H, NuSTAR and Spectrum-Roentgen-Gamma, which are expected to fly in few years, will certainly provide important contributions to address some of the topics concerning the origin of the hot gas, the properties of the GC hard source populations, the role of reflection in producing the 6.4 keV line and the hard X-rays in the GC region.

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