COMPACT AND DIFFUSE SOURCES IN THE GALACTIC CENTER REGION

E. Churazov 1,2, M. Gilfanov 1,2, R. Sunyaev 1,2, S. Kuznetsov 2

1) MPI fur Astrophysik, Karl-Schwarzschild-Strasse 1, 85740 Garching, Germany
2) Space Research Institute (IKI), Profsouznaya 84/32, Moscow 117810, Russia

ABSTRACT The 10 by 10 degrees region around dynamic center of our Galaxy is known to host a large number of bright X-ray sources, most of which are low mass binary systems. While high luminosity Z-sources are especially bright in the standard X-ray band (e.g. 2–10 keV), lower luminosity systems are dominating the flux above 30 keV. The two hardest sources in the region, i.e. 1E1740.7–2942 and GRS 1758–258 are thought to be black hole candidates (BHC) based on the similarity of spectral properties and short-term variability to that of dynamically proven BHCs. However, while most of the other galactic BHCs are known to be transients, these two objects could be considered persistent though variable sources. The persistent behavior of these sources implies some constraints on the parameters of the binary systems. Both sources were detected in the first GRANAT observation of the GC region. They are the only two persistent BHCs seen in the 35-75 keV SIGMA image after collecting several million seconds of exposure time over eight years, indicating that they are perhaps the only two persistent BHCs in the region.

Another peculiar object in the field is of course a putative supermassive black hole (Sgr A*) at the dynamic center of our Galaxy. The present day’s X-ray luminosity from Sgr A* is very small ($< 10^{36}$ erg/s). However an indication that Sgr A* might have been much brighter in the past was found while studying diffuse X-ray emission in the region. We speculate here on how future X-ray observatories may verify the hypothesis of the violent activity of Sgr A* in the past.

KEYWORDS: scattering - stars: binaries: general - Galaxy: center - X-rays: general

1. COMPACT SOURCES

The Galactic Center (hereafter GC) is a densely populated region of the sky. Few dozen bright sources are known within 5-6 degrees from the GC. A large fraction of these sources are low mass binary systems (LMXB) containing a neutron star or a black hole. Shown in Fig.1 are the images taken in the standard (2-20 keV, TTM/KVANT, see also Ubertini et al., 1999 for the BeppoSAX/WFC results) and hard (35-75 keV, SIGMA/GRANAT) energy bands. Both images have a similar dynamic range (flux ratio of the brightest and weakest sources shown in the image) of $\sim$10–20 and contain a comparable number of bright sources. Remarkably, the subsamples of sources seen in the two energy bands are very different. In fact the X-ray burster GX354–0 is the only source seen as a bright object in both images. The reason for that is clear from Fig.2, where the spectra of typical LMXB sources
FIGURE 1. The Galactic Center region in the standard 2-27 keV (TTM/KVANT) and hard 35-75 keV (SIGMA/GRANAT) bands. Both images have roughly the same dynamic range (flux ratio of the brightest and weakest sources shown in the image) of $\sim 10^{-20}$. The exposure time is $\sim 4000$ s and $6 \times 10^6$ s for the TTM and SIGMA images respectively. For the standard X-ray band the image was cut below 5$\sigma$ level (corresponding to the flux of $\sim 15$ mCrabs at the center of the image) and for the hard band the image was cut below 4.5$\sigma$ level (corresponding to the flux of $\sim 5$ mCrabs at the center of the image).

from the GC region are shown. High luminosity LMXBs with a neutron star (Z-sources, Fig.2 left) are very bright in the standard X-ray band, but are very weak above $\sim 30$ keV. On the contrary BHCs (Fig.2 right) have peak luminosity at the energy of $\sim 100$ keV, while in standard X-ray band they are relatively weak. An intermediate group is constituted by lower luminosity LMXB with a neutron star (typically X-ray bursters, Fig.2 middle), which are often switched between softer and harder states. The latter sources appear part of the time as bright objects in the standard X-ray band and part of the time as bright objects in the hard band. Even in the hard state spectra of X-ray bursters are still softer (in terms of the energy at which maximum luminosity is emitted) than those of BHCs (e.g. Goldwurm et al. 1994, Gilfanov et al. 1995, Churazov et al., 1997). Indeed, using the optically thin plasma emission model to crudely characterize hardness of source spectra in the 35-150 keV band, one can conclude that best fit temperatures to the spectra of each NS LMXB seen in the SIGMA image (Fig.1) are clustered around 50 keV or below, while best fit temperatures for BHCs (e.g. 1E1740.7-2942, GRS1758-258) are all around 100 keV or above.

The 1E1740.7-2942 and GRS1758-258 are the hardest sources in the field, having peaks of the spectra ($\nu F_{\nu}$ in units keV$^2$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$) at the energy of $\sim 100$ keV. Their spectral properties resemble those of the dynamically proven BHCs. However while most of the BHCs in the Galaxy are transients, 1E1740.7-2942 and GRS1758-258 are certainly persistent though variable sources. Shown in Fig.3 are the 40–150 keV light curves of 1E1740.7-2942 and the transient GRS1716-249 (Nova
FIGURE 2. Typical spectra ($\nu F_\nu$ in units $keV^2 \ cm^{-2} \ s^{-1} \ keV^{-1}$) of high luminosity neutron star LMXB GX 5–1 (left, TTM/KVANT), X–ray burster GX354-0 in two spectral states (middle, RXTE) and black hole candidate 1E1740.7–2942 (right, ASCA, SIGMA/GRANAT).

Oph 93 – also located in the GC region) for most of SIGMA observations in 1990–1998. It is clear that the light curve of 1E1740.7-2942 is much closer to the light curve of Cyg X–1 (see e.g. Kuznetsov et al., 1997), than that of a typical X–ray transients. The same is true for GRS1758-258. However Cyg X-1 has a very massive companion and accretion is fed by a stellar wind. At least for GRS1758-258 the hypothesis of the companion massive enough to produce sufficient stellar wind can be rejected based on the optical and infrared limits (see e.g. Chen, Gehrels & Leventhal, 1994; Marti et al., 1998).

During the last few years the hypothesis explaining the “transient” character of the black hole LMXBs due to the thermal–viscous instability of an accretion disc in the zone of partial hydrogen ionization was intensively discussed in the literature (see e.g. Van Paradijs 1996, King et al. 1997a, Dubus et al. 1998). This instability was successfully applied to cataclysmic variables (e.g. Meyer and Meyer-Hofmeister 1981). It is interesting to understand the role of this instability for the GRS 1758-258 and 1E1740.7-2942 sources (Kuznetsov et al., 1998). The light curves of GRS 1758-258 and 1E1740.7-2942 seem to indicate that this instability is suppressed in these objects. Menou, Narayan & Lasota (1998) suggested that a population of faint non-transient LMBHBs can exist in the Galaxy. In their non-transient sources the outer regions of the disk are colder than the ionization temperature of hydrogen while at smaller radii disk switches to the stable advection dominated solution before the disk temperature rises to the critical value. However expected luminosities of such objects are much smaller than observed values ($\geq 10^{37} \ erg/s$) for GRS 1758-258 and 1E1740.7-2942. Another possibility is to assume that even at the outmost regions of the accretion disk the temperature is already above the hydrogen ionization temperature. Unlike CVs for accreting black holes the irradiation of the outer part of the accretion disc by the X-rays (e.g. Shakura & Sunyaev 1973, Lyuty & Sunyaev 1976) originated in the inner part of the disk might be important for suppressing this instability (e.g. Van Paradijs 1996, King et al. 1997a, 1997b, Dubus et al.
Using their prescriptions for suppression of the instability (in the form of minimal mass accretion rate as a function of radius) one can place a constraint on the orbital period of the binary, assuming that outmost radius of the disk corresponds to some fraction of the primary Roche lobe radius. For reasonable choice of the black hole mass and mass ratio the period must be less than 10-20 hours and the mass accretion rate in GRS1758-258 and 1E1740.7-2942 should be in the range $\sim 10^{17} - 10^{18} \text{ g/s}$. The above estimate is based on the results of calculations of Dubus et al., 1998. Note however that there are many uncertain parameters in the model which might affect these estimates. Use of the prescription of King et al. 1997b leads to a more tight constraint on the binary period ($P_{\text{orb}} \leq 7$ hours). The assumption that only local viscous energy release affects the temperature and the structure of the disc (i.e. no irradiation) imply even stronger limit on the period $P_{\text{orb}} \leq 3-5$ hours. Short period BH transients are known (e.g. GRO J0422+32 has $P_{\text{orb}} = 5.1$ hours), but it is interesting that mass accretion rate of $\sim 10^{17} - 10^{18} \text{ g/s}$ (sustained by GRS1758-258 and 1E1740.7-2942 at approximately the same level for at least 10–20 years) is two orders of magnitude higher than the averaged mass accretion rate for transient sources (see e.g. Van Paradijs 1996). This may be related with the different type of companion stars in GRS1758-258 and 1E1740.7-2942 and BHC transients. On the other hand many persistent neutron star binaries are know with luminosities in the range of $10^{37} - 10^{38} \text{ erg/s}$ (i.e. $\dot{M} \sim 5 \times 10^{16} - 5 \times 10^{17} \text{ g/s}$). Using this empirical fact one can further speculate that GRS1758-258 and 1E1740.7-2942 might be the systems with low masses of the black holes, compared to the higher black hole masses in the transient systems.

It is interesting that 1E1740.7-2942 and GRS1758-258 were detected in the very first GC observation by SIGMA in 1990. But even after adding more than 100 observations over 1990–1998 these two objects remain the only persistent BHCs in the GC field, although the sensitivity increased by a factor of $\sim 10$. The only other BHC seen in the averaged 1990–1998 image is GRS1716–249 (an X–ray transient Nova Oph 93), which was bright for only a short period of time. This result suggests that persistent black holes are rare objects and even with increased INTEGRAL sensitivity 1E1740.7-2942 and GRS1758-258 may remain the only two persistent BHCs in the field. The absence of weaker BHCs in the GC field may also imply some constraints on the luminosity function of the persistent black hole candidates in the hard state.

2. DIFFUSE EMISSION – EVIDENCE FOR SGR A* ACTIVITY

While at least three stellar mass BHCs are seen in the averaged 35–75 keV SIGMA image (Fig.1) there is no evidence for strong X–ray emission from the dynamic center of the Galaxy. The nonthermal radio source Sgr A*, which presumably coincides with a supermassive ($\sim 2.5 \times 10^6 \text{ M}_\odot$, e.g. Eckart & Genzel, 1996) black hole is a very weak object in X–rays. The best X–ray imaging of the Sgr A* vicinity so far has been done with ROSAT (Predehl & Truemper, 1994) resolving the 1E1742.5-2859 source (usually associated with Sgr A* X–ray emission) into three components, one
FIGURE 3. The long term light curves of two black hole candidates in the Galactic Center region. GRS 1716–249 (X-ray Nova Oph 93) is a transient source with a small duty cycle. On the contrary 1E1740.7–2942 was radiating in the hard X-rays at approximately the same level during most of the SIGMA/GRANAT observations in 1990–1998. Another non–transient black hole candidate in the region – GRS1758-258 has a light curve similar to that of 1E1740.7–2942.

of which coincides (within 10") with the position of the radio source Sgr A* (See also Sidoli et al., 1999 for the results of recent deep observations of BeppoSAX). The intrinsic luminosity of the source in this energy band (1.2–2.5 keV) is uncertain because of the strong interstellar absorption and ranges from less than 10^{35} to 7 \times 10^{35} erg/s, depending on the adopted value of the absorbing column density. At higher energies (2-200 keV) the absorption is not so important, but the spatial resolution (typically few arcminutes) is significantly worse than that of ROSAT and detected fluxes may be contaminated by other sources. In any case the conservative upper limit on the X–ray luminosity of the Sgr A* does not exceed few 10^{36} erg/s. This value is some 10^{8} times lower than the Eddington limit for a \sim 2.5 \times 10^{6} M_{\odot} black hole.

While the present day X–ray luminosity of Sgr A* is small, some indication of a past violent activity of the Sgr A* were found. Observations of the diffuse emission
FIGURE 4. **Left:** Schematic view of the regions having similar time delay for the radiation emitted by the source during a short flare and scattered by the gas in the molecular clouds before reaching the observer. Only clouds located along the surface of the parabola will be bright in the reprocessed radiation at a given moment of time. **Right:** Morphology of the 6.4 keV line surface brightness distribution as a function of time and relative position of the scattering cloud and the compact source of continuum radiation. Time evolution assumes a short flare of continuum emission. The time tags marked in the left column indicate the time elapsed since the moment, when the surface of the illuminating parabola touched the cloud for the first time. The intensity of the the primary source was adjusted for each column in order to have the same total flux from the cloud for the row marked ‘30'(years). The position of the cloud with respect to the source is indicated by the pair of numbers at the bottom of the figure. E.g. (0; 0) corresponds to the source at the center of the cloud; (−100; 200) corresponds to the cloud which is shifted by 100 pc to the left from the source and is located 200 pc further away from the observer than the source. Density distribution in the cloud adopted from Lis and Goldsmith, 1989.

in the 8–22 keV energy range, elongated parallel to the Galactic plane (Sunyaev et al., 1993) and detection of the strong 6.4 keV fluorescent line with ~ 1 keV equivalent width from Sgr B2 complex and few other clouds in the Galactic Center region (Koyama, 1994, 1996) suggest that the neutral matter of these clouds is (or was) illuminated by powerful X-ray radiation, which gave rise to the reprocessed radiation. It is important to stress that the large value of the 6.4 keV line equivalent width detected by ASCA from the Sgr B2 cloud suggests that we observe an almost pure reprocessed component without direct emission from the source. It is therefore likely that this source is now in a weak state. One of the interesting hypothesis suggests that reprocessed radiation was produced by a short outburst of the X-ray emission from Sgr A* few hundred years ago. Simple estimates show that Sgr A* luminosity at the level of $10^{39}$ erg/s is required to power fluorescent emission from the Sgr B2 cloud (i.e. well in the range allowed by the Eddington limit for this object). We consider below a few simple observational tests which could verify this hypothesis.

The simplest test (AXAF, XMM, ASTRO-E) would be to look for time depen-
dent changes of the surface brightness of the reprocessed radiation (e.g. in the 6.4 keV line, see Sunyaev & Churazov, 1998). Indeed, for the short flare the reprocessing sites (bright at a given moment of time after the primary flare) should be located at the surface of the parabola with a focus at the position of the primary source (Fig.4). All points over the surface of this parabola have the same time delay for the photons coming from the source to the reprocessing site and then to the observer. The parabola will evolve with time effectively scanning the nonuniform distribution of the scattering medium around the Sgr A*. The apparent motions could be sub or superluminal, depending on the mutual location of the primary source and the scattering site. Shown in Fig.4 are the time dependent changes of the surface brightness of a spherical cloud at different moments of time and different position of the cloud. For the GC region one can expect “proper motion” of the regions bright in the 6.4 keV line at a rate of the order of an arcminute per year (if the rise and decay fronts of the flare were sharp enough).

Important information can be obtained by studying the spectra of the reflected component. Shown in Fig.5 is a spectrum reflected by a semi-infinite slab of a molecular gas having solar abundance of heavy elements. It is similar to the frequently used “reflection” model, but fluorescent lines of the most abundant elements (not only iron $K_{\alpha}$) are taken into account and electrons are assumed to be bound in hydrogen molecules. Measurement of precise energies of the fluorescent lines

FIGURE 5. **Left:** Reflection spectrum for a semi-infinite slab of neutral gas (hydrogen is in a molecular form) illuminated by a power law spectrum (shown by dashed line). **Right:** High energy part of the reprocessed spectra (under assumption of an optically thin cloud) for the different scattering angles (180°, 90°, 45°, 0° from bottom to top). The incident spectrum was assumed to be a power law with a photon index of 1.8 extending up to an energy of 1.5 MeV. Normalization of the reflected component depends on a solid angle occupied by the cloud and its optical depth.
(ASTRO-E, Constellation, XEUS) will allow direct comparison of the X–ray data and CO maps (velocity resolved) in radio. It will be possible to unambiguously identify the clouds, responsible for reprocessed radiation with the features in the CO maps. Note that electrons bound in molecules cause an increase of the reflected continuum by a factor of 2 below 4–5 keV (due to coherent scattering by electrons bound in hydrogen molecules) and smearing of the “Compton shoulder” at the low energy side of the bright emission lines (due to the “motion” of bound electrons within molecules).

One can try to identify the clouds already passed by a “parabola” of a primary radiation, using high sensitivity, high resolution spectroscopy (Constellation, XEUS). Indeed, even although primary photons already left the cloud, some fraction (of the order of Thomson optical depth of the cloud) of the reprocessed photons will be “reprocessed” again and reach the observer after an additional delay of the order of light crossing time of the cloud (we consider here the case of an optically thin cloud). The flux seen by the observer will of course decline with time, but the equivalent width of the fluorescent lines will on the contrary increase (Sunyaev & Churazov, 1998). The possibility of the detection of such delayed emission may be severely limited by the very extended low density envelopes of the clouds, leading to sufficiently strong contribution of the reprocessed emission from the gas located further away from observer and still exposed to the primary emission of the source.

If the spectrum of Sgr A* was hard and extended up to MeV, then the shape of the continuum emission of the reflected component can be used to determine the relative position of the scattering medium and the primary source (Fig.5). Indeed in the limit of an optically thin cloud the energy of a cut-off in the spectrum of the reflected component is defined by the scattering angle, simply because the energy of high energy photons after Compton scattering by a cold electron strongly decreases if the scattering angle is large. Therefore a detail study of the high energy continuum in the region with INTEGRAL and correlation with the data in the standard X–ray band may help to determine the relative position of the clouds with respect to the Sgr A* and constrain the hard luminosity of the putative flare of Sgr A*.

ACKNOWLEDGMENTS This work was supported in part by RBRF grants 96-02-18588 and 97-02-16264. The SIGMA results are presented on behalf of the SIGMA team (IKI, Moscow; SAp, Saclay; CESR, Toulouse).

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