The Galactic Center – an AGN on a starvation diet

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ABSTRACT

The Galactic Center shows evidence for the presence of three important AGN ingredients: a Black Hole ($M \sim 10^6 M_\odot$), an accretion disk ($10^{-8.5} - 10^{-7} M_\odot/yr$) and a powerful jet (jet power $\geq 10\%$ disk luminosity). However, the degree of activity is very low and can barely account for the energetics of the whole central region. Nevertheless, in the very inner arcsecond the central engine becomes dominant and provides an interesting laboratory for the physics of central engines (Black Holes) in galactic nuclei. We therefore give an overall picture of the central arcsecond where we link the radio emission and the heating of the ambient medium to a weakly accreting disk surrounding a massive Black Hole.

1 INTRODUCTION

The dynamical center of the Galaxy is the radio point source Sgr A*, which is also the center of the central star cluster (Eckart et al. 1993). Investigations of the enclosed mass in the central region show that there is evidence for a mass concentration of the order of $10^6 M_\odot$ within the central arcsecond (Genzel and Townes 1987). There is good reason to assume that this “dark mass” indeed is the mass of a massive Black Hole (BH) powering Sgr A*. The total spectrum of this source from radio to NIR was compiled by Zylka et al. (1992). There is a flat radio spectrum up to 7mm, and a steeply rising submm spectrum, which Zylka et al. interpret as thermal emission from a dust torus surrounding the BH. In the FIR one finds a spectral break at 30$\mu$m indicated by upper limits and a third spectral component rising in the NIR, which has been interpreted as emission from an accretion disk around the BH.

2 HERTZSPRUNG-RUSSELL DIAGRAM FOR THE SGR A* DISK

Because of strong obscuration in the galactic plane we probably will never be able to measure exactly the optical and UV part of Sgr A*, which is needed to discriminate between different disk models. Nevertheless, there are a number of parameters we can infer by indirect means to constrain possible models. For example, we know that in the outer part of the Galactic Center region almost 50% of the starlight is...
Fig. 1—HR diagrams for BHs. The figure on the left gives an overview for the whole parameter range of astrophysically relevant BHs. The small areas cover all possible values for effective temperature and luminosity of a BH of given mass and accretion rate but different inclination angles and angular momenta \( a \). Areas at the same horizontal line have the same absolute accretion rate, areas at the same diagonal line from lower left to upper right have the same mass and areas at the same diagonal from the lower right to the upper left have the same accretion rate in terms of their Eddington rate. The boxes denote schematically the position of AGN, Sgr A* and stellar mass BHs. The figure on the right is a zoomed version of the HRD, however, for an edge-on disk and a fixed BH mass of \( 2 \cdot 10^6 M_\odot \).

absorbed in the interstellar dust (Cox & Mezger 1989). IR measurements show that the dust concentration strongly peaks around Sgr A*, therefore we assume that all the luminosity of Sgr A* beyond the NIR is absorbed in the dust and reradiated at longer wavelength. Zylka et al. estimated the total luminosity in the central 30” to be \( 1.5 \cdot 10^6 L_\odot \). Interestingly the total luminosity of the stellar star cluster, as extrapolated from the outer parts (Falcke et al. 1993a) is of comparable order, thus one obtains an upper limit for the disk luminosity of \( L_{\text{disk}} < 7 \cdot 10^5 L_\odot \). Further limits for \( L_{\text{disk}} \) and the effective temperature \( T_{\text{eff}} \) can be found by assuming that the NIR measurements represent the Rayleigh-Jeans tail of a Black-Body, leading to \( L_{\text{disk}} > 7 \cdot 10^4 L_{\text{disk}} \) and \( 20,000 \text{K} < T_{\text{eff}} < 40,000 \text{K} \).

If we construct a HR-diagram for BHs (Falcke et al. 1993a), we find that for a given BH mass of \( 2 \cdot 10^6 M_\odot \) the data is consistent with a maximally rotating BH accreting \( 10^{-7} - 10^{-8.5} M_\odot / \text{yr} \) in a disk seen edge on (Fig. 1). A lighter BH with \( M_\bullet = 10^3 M_\odot \) does not fit the current data at all. The accretion rate we find is more than 5 orders of magnitude lower than the Eddington limit of the BH and 7 orders of magnitude lower than in average AGN – the Galactic Center resembles an AGN on a starvation diet.
3 BLACK HOLE H II REGION

To learn more about the hidden UV spectrum of Sgr A*, one has to apply indirect methods, i.e. the heating and ionization of ambient gas by the disk spectrum. From the HR diagram one can see, that the disk is at the edge of producing an appreciable amount of ionizing UV photons, therefore the state of the ambient gas will be very sensitive towards changes of the parameters in the BH/accretion disk system. To test this we took the photoionization code HOTGAS developed by Schmutzler & Tscharnuter (1993) to calculate gas temperatures of a test cloud with constant density at different spatial positions around Sgr A* neglecting all dynamical and optical depth effects (Fig. 2).

For a set of parameters with $M_*=10^6\, M_\odot$, $\dot{M}=10^{-7}\, M_\odot/\text{yr}$ and a maximally rotating BH, we find a very anisotropic temperature distribution, which reflects the relativistic beaming of the disk spectrum at high inclination angles, heating the gas to temperatures of $T_{\text{gas}} \geq 10^{5}$ K. A moderate change of the angular momentum of the BH from $a=0.9981$ to $a=0.9$ would be enough to suppress the heating almost completely. On the other hand, a low mass BH (e.g. $10^3\, M_\odot$) inevitably leads to much higher temperatures ($10^5 - 10^6$ K) in the inner arcsec of the Galactic Center. No configuration is able to heat the total H II region Sgr A*. Nevertheless, once we are able to determine temperature and density distribution of the gas in the inner arcsecond of the GC we will have a powerful tool to discriminate between different models.
4 SGR A*: A JET?

After having shown that the IR-NIR spectrum is consistent with the presence of an accretion disk, it is straightforward to postulate the existence of a radio jet created at the inner edge of the disk producing the compact flat spectrum radio emission – a feature seemingly related to disks. This jet/disk link directly imposes an important constraint: The jet can not carry away more matter and more energy than is provided by the accretion process.

We adopt the Blandford & Königl (1979) jet model, which assumes a conically expanding, supersonic jet, with constant velocity and an internal gas pressure dominated by a turbulent magnetic field being in energy equipartition with relativistic electrons.

To account for the jet/disk link, we express the mass loss due to the jet $\dot{M}_{\text{jet}}$ and the total energy of the jet $Q_{\text{jet}}$ in terms of the disk accretion rate $\dot{M}_{\text{disk}}$, such that

$$Q_{\text{jet}} = q_j \dot{M}_{\text{disk}} c^2 \quad \text{and} \quad \dot{M}_{\text{jet}} = q_m \dot{M}_{\text{disk}}.$$  

(1)

Using the above parameterization, we find for the flux of Sgr A* a flat spectrum with $F_{\nu} = \text{const}$ and an absolute value of

$$F_{\nu} = 1 \text{ Jy} \cdot D(i, \gamma_j)^{13/6} \sin^{1/6} \left( \frac{M}{3} \right)^{-11/6} \left( \frac{\Lambda}{9} \right)^{-5/6} \left( \frac{\dot{M}_{\text{disk}}}{10^{-7} M_\odot/\text{yr}} \right)^{17/12}.$$  

(2)

Here $D$ is the Doppler factor, $i$ the inclination of the jet axis, $M$ the Mach number of the jet, $\beta_j$ the velocity of the jet, $\gamma_j$ the relativistic $\gamma$ factor of the jet and $\Lambda$ a logarithmic correction factor describing the relativistic electrons.

We see that even with the extremely low accretion rate in Sgr A* it is possible to feed a radio jet producing 1 Jy emission with a reasonable set of parameters. However, an appreciable fraction of the total mass accretion rate ($\geq 3\%$) has to be expelled by the jet. Using the energy equation of this system (Falcke et al. 1993b) this translates to a jet power of $Q_{\text{jet}} \geq 4\% \dot{M}_{\text{disk}} c^2$. Thus the ratio of the total jet power to the disk luminosity $L_{\text{disk}} \leq 30\% \dot{M}_{\text{disk}} c^2$ has a lower limit of $Q_{\text{jet}} / L_{\text{disk}} \geq 12\%$.

Alas, there is a problem: for 20 years now, VLBI radio observations tell us that Sgr A* is a point source at all wavelengths. How can this be a jet? An answer is found by examining the structural predictions of the jet/disk model. The physical scale of the synchrotron emission depends inversely on frequency yielding for the Sgr A* set of parameters

$$z \simeq 2 \cdot 10^{13} \text{cm} \left( \frac{43 \text{GHz}}{\nu} \right) \left( \frac{\gamma_j \beta_j}{\sqrt{1 + (\gamma_j \beta_j)^2}} \right) \left( \frac{9}{\Lambda M 3%} \right)^{1/2} \left( \frac{\dot{M}_{\text{disk}}}{10^{-7} M_\odot/\text{yr}} \right)^{2/3}.$$  

(3)

For the low accretion rate of Sgr A*, the scale of the jet then is smaller than the resolution of VLBI even at 43 GHz. Thus, one should see at best a marginally resolved
central core. And indeed, this is confirmed by recent 43 GHz VLBI observations of Sgr A* (Krichbaum et al. 1993), where the emission is still dominated by an unresolved central core which, however, is slightly elongated suggesting an underlying jet structure.

There is another interesting observational consequence associated with equation (3). We can turn the argument around and ask: What is the shortest possible wavelength \( \lambda_{\text{break}} \) emitted by such a jet, namely the one emitted at the shortest length scale. For a given central mass, the smallest possible scale is the scale of a BH which is \( R_g = 1.5 \cdot 10^{11} M_\odot / 10^6 M_\odot \) cm. A reasonable and conservative guess for the smallest jet scale then also would be of the order of several \( R_g \), say \( z_{\text{min}} \geq 10 \cdot R_g \). For a \( 10^6 M_\odot \) BH we obtain \( \lambda_{\text{break}} \leq 560 \mu m \) and for a \( 10^3 M_\odot \) BH we obtain \( \lambda_{\text{break}} \leq .56 \mu m \). For wavelength shorter than \( \lambda_{\text{break}} \) we would expect to see a steepening of the spectral index from 0 to -0.5 or even steeper.

This explains very well the observed lack of far infrared emission (shortwards 30\( \mu \)m) from Sgr A* if there is indeed a \( 10^6 M_\odot \) BH. On the other hand, there is no such argument for a \( 10^3 M_\odot \) BH. As the break frequency should in this case be somewhere in the NIR we would rather expect a continuing flat spectrum visible also in the FIR, which is not observed.

4 CONCLUSIONS

Spectral and structural information of Sgr A* are consistent with the standard AGN triad Black Hole, jet and accretion disk, with converging evidence for a supermassive Black Hole \( (10^6 M_\odot) \), low accretion rate \( (10^{-8.5} - 10^{-7} M_\odot / \text{yr}) \) and a powerful radio-jet (as compared to the disk luminosity). This set of parameters is consistent with the NIR data, the dust luminosity, the radio spectrum, the size of the radio source and the lack of non-thermal FIR emission.

However, one question is still unanswered: Why is the central accretion rate so extremely low? Which mechanism prevents the large amount of gas in this region from being accreted onto the BH?

A plausible explanation would be to assume that the accretion process varies strongly radially and in time. Thus the central accretion rate could have been much higher in earlier epochs. A dust torus in the inner arcsecond – as suggested by submm observations – could be just the outer part of a non-stationary accretion disk, serving as a reservoir where matter is temporarily stored until stronger accretion process in the inner parts sets in again.

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