The Galactic Center radio jet

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Abstract. Recent observations of the radio and NIR source Sgr A* reinforce the interpretation of the Galactic Center as a scaled down version of an AGN. The discovery of an elongated structure at 43 GHz and increasing evidence for the presence of an accretion disk surrounding a Black Hole lead us to assume that both, an accretion disk and a jet, are present in the Galactic Center and are physically linked. We model the radio emission of Sgr A* successfully with a Blandford & Königl type jet and analyze the energetics of the coupled jet-disk system in Sgr A* where jet and disk are parametrized in terms of the accretion power. With this method we are able to confirm independently the lower limit of the Sgr A* accretion rate $\dot{M} \gg 10^{-8.5} M_{\odot}$ found previously. Moreover, using the limits imposed by observational data, we show that within such a jet-disk model, the total jet power $Q_{\text{jet}}$ is of comparable order as the radiated disk luminosity $L_{\text{disk}}$. A jet model together with the assumption of an $10^{6} M_{\odot}$ Black Hole also qualitatively explains the submm excess and the lack of non-thermal IR radiation. The small size of the visible part of the jet (< 1 mas) is due to the low accretion rate of Sgr A*.

Key words: Galaxy; center – Galaxies: active – Galaxies: jets – Galaxies: nuclei – Accretion disks – Black Hole physics

1. Observations of Sgr A*

A prominent phenomenon in the Galactic Center is the compact, non-thermal radio source Sgr A* (Balick & Brown 1974, Lo et al. 1985), showing a fairly flat ($S_{v} \propto \nu^{-0.3}$) spectrum in the range 1 to 230 GHz (eg. Zyka & Mezger 1988). Eckart et al. (1992) and Rosa et al. (1992) have detected Sgr A* at $\lambda 2.2 \mu m$ and $\lambda 1 \mu m$ wavelengths providing evidence for a luminous central object radiating also at optical wavelength. Zyka et al. (1992) explain their $\lambda 1300 \mu m$ and $\lambda 870 \mu m$ continuum observations of the Sgr A* region by the existence of a thermal dust disk surrounding Sgr A* or a self-absorbed compact synchrotron source. Falcke et al. (1993) explain the NIR data with a rotating Black Hole of mass $M_{*} \sim 10^{6} M_{\odot}$ surrounded by a hot accretion disk seen edge-on. And finally, as another breakthrough, Krichbaum et al. (1993) succeeded in detecting Sgr A* with VLBI at 7mm. For the first time a resolved picture of this non-thermal radio source suggests an elongated structure on a scale of a few mas corresponding to an observed linear size of several $10^{14} \text{cm}$ inclined at $\sim 55^\circ$ to the galactic plane.

2. The jet-disk coupling

2.1. Parametrization of the jet-disk model

We now want to investigate whether the elongated radio structure in Sgr A* can be interpreted as a radio jet. It is commonly believed that radio jets originate from an accretion disk surrounding a star, neutron star or a Black Hole. As there are also strong hints for emission from an accretion disk in Sgr A* (see above) that assumption may be valid for the Galactic Center as well, providing us with observational information for both systems. We therefore develop a jet model with regard to the coupling of jet and disk and the constraints imposed by observation.

Within such a jet-disk model, we express the basic properties of the radio jet in units of the disk accretion rate $M_{\text{disk}}$ of Sgr A*. The maximum accretion power $Q_{\text{accr}}$ is given by the rest energy at infinity of the matter $M_{\text{disk}}c^{2}$. The total radiated disk luminosity $L_{\text{disk}}$ is an appreciable fraction $q_{d}$ of this accretion power and in the case of a Black Hole as the central object will be in the range $q_{d} \sim 5\% - 30\%$ (Thorne 1974). Likewise, the total jet power $Q_{\text{jet}}$ including the rest energy of the expelled matter – should be a fraction $q_{j} < 1$ of the accretion power and also the mass loss rate due to the jet $\dot{M}_{\text{jet}}$ is a fraction $q_{m} < 1$ of the mass accretion rate in the disk. Thus we define

$$Q_{\text{accr}} = M_{\text{disk}}c^{2}, \quad q_{d} = \frac{Q_{\text{jet}}}{Q_{\text{accr}}}, \quad q_{a} = \frac{L_{\text{disk}}}{Q_{\text{accr}}}, \quad q_{m} = \frac{M_{\text{jet}}c^{2}}{Q_{\text{accr}}}.$$ (1)

The $q_{a,j,m}$ are dimensionless parameters, while $Q_{\text{accr}}$ defines the physical scale of the system; $c$ denotes the speed of light. We neglect all other energy consuming processes so that the remaining energy $(1 - q_{d} - q_{a})Q_{\text{accr}}$ is swallowed by the Black Hole.

2.2. Basic assumptions of the jet-disk model

The above quantities are all measured in the observer’s frame; we will now switch to the rest frame of the jet and use this parametrization to calculate the radio emission of Sgr A* as emission from a radio jet and analyze its possible link to the accretion process. As the structural information about the Sgr A* radio emission is still uncertain, we will use the simplified Blandford & Königl (1979) jet model which was developed...
initially for the unresolved core of AGN jets. The basic idea is that the radio emission is produced by a supersonic, freely expanding, therefore conical jet with semi-opening angle \( \phi \) and constant velocity \( \beta_j \), convecting a tangled magnetic field dominating the internal gas pressure and producing a powerlaw energy distribution of relativistic electrons via shock acceleration. It is assumed that there is an approximate equipartition between the magnetic energy density \( u_{\text{mag}} = B^2/8\pi \) and the relativistic particle energy density \( u_{\text{rel}} \). In the following we will use cylindrical coordinates, denoting the axis along the jet as \( z \) and the distance from the axis to the boundary surface of the jet-cone as \( r = z \sin \phi \). We discuss only the part of the jet far away from its footpoint.

For this model one usually takes an electron distribution of the form \( N(\gamma_e) = K\gamma_e^{-2} \) for relativistic electron \( \gamma \)-factors in the range \( \gamma_{\text{min}} \leq \gamma_e \leq \gamma_{\text{max}} \). From \( u_{\text{rel}} \approx u_{\text{mag}} \) we get \( K = B^2/(8\pi m_e c^2 \Lambda) \), where \( m_e \) is the electron mass and \( \Lambda = \ln((\gamma_{\text{max}}/\gamma_{\text{min}})) \) yielding a number density for electrons of \( n = B^2/(8\pi \gamma_{\text{min}} m_e c^2) \).

The energy density and the pressure in the jet is assumed to be mainly due to the magnetic field and the relativistic particles \( p = u_{\text{mag}} + u_{\text{rel}} \approx (B^2/8\pi)(1 + \frac{1}{\beta_j^2}) \). Actually the factor \( \frac{1}{\beta_j^2} \) is valid only for the extreme relativistic case where \( p_{\text{rel}} = \frac{1}{\beta_j^2} \) and exact equipartition, however, it can only be as high as \( \frac{1}{\beta_j^2} \) in the nonrelativistic case or negligible for \( u_{\text{rel}} \ll u_{\text{mag}} \). Thus our choice of \( p \) is a fair approximation.

An important parameter of the jet flow is its proper Mach number \( M = \beta_j/\beta_{\text{min}} \). For a free jet the minimum opening angle is given by its Mach angle, which is defined as \( \sin \phi_{\text{min}} = 1/\Lambda \) (Königl 1980). For a perfect gas we have: \( \gamma = 1/(1 - \beta_j^2) \), \( \beta_j = (\gamma - 1)/(\gamma + 1) \), \( \beta_{\text{min}} = 1 \), and the enthalpy density \( \omega = m_e c^2 + \gamma p/(\gamma - 1) \) if we demand equal numbers of thermal protons and relativistic electrons (cf. last paragraph of this section). Here we expect \( M_{\text{min}} \approx \frac{m_p}{m_e} \) and thus

\[
M = \frac{\gamma_j \beta_j}{\sqrt{\frac{4m_e}{3m_p}\gamma_{\text{min}}}},
\]

for the other extreme we would get a maximum sound velocity \( \beta_{\text{max}} = \sqrt{(1 - \gamma_j)/\gamma_j} \) and the condition \( M > \gamma_j \beta_j / \beta_{\text{max}} \).

Considering that the particle flux of the jet is given by \( q_m Q_{\text{acc}}/m_e c^2 = \gamma_j n \beta_j c \pi r^2 \), we can now express the magnetic field in the jet in terms of the numbers \( q_m \) and \( M \), obtaining the familiar \( B \propto z^{-1} \) behaviour.

\[
B = \left( \frac{6\gamma_j \beta_j q_m Q_{\text{acc}}}{\Gamma M z^2 \sin \phi_j c^2} \right)^{1/3}
\]

The assumption of Blandford & Königl that all electrons are relativistic and all protons are thermal is very crude and we would rather expect to have a mixture of a thermal and a relativistic plasma both containing electrons and protons. But if the ratio of thermal protons to nonthermal electrons is constant throughout the jet, this effect will cancel out in the final equations and only the definition of \( \Lambda \) and \( M \) in Eq. (3) will change. We therefore will not use Eq. (2) in this Letter and rather consider \( M \) and \( \Lambda \) as free parameter which in principle contain all the unknown microphysics (e.g. the electron to proton ratio). We leave a more elaborated discussion of this point to a subsequent paper.

2.3. Energy equation of the jet-disk model

To investigate how much energy is extracted by the jet relative to the disk, we have to write down the basic energy equation for the jet-disk system. This is simply the relativistic Bernoulli equation for the jet \( \gamma \omega/n = \omega/n_{\infty} \) with the left hand side parametrized by the quantities \( q_m \) and \( M \) and the right hand side determined by the energy supply from the accretion process and parametrized by \( q_j \). Algebraic transformations then lead to

\[
\gamma q_m \left( 1 + \frac{\gamma_j^2 \beta_j^2}{(\Gamma - 1)M^2} \right) = q_j.
\]

If we subtract the rest energy from both sides and take the non-relativistic limit, this equation simply states that the total power in the jet consists of the power in relativistic particles and the magnetic field plus the kinetic energy of the matter.

2.4. Radio emission from the jet

To deduce some of the parameters of the jet-disk system from the observation we now have to calculate the synchrotron emission from the jet described above. Angle averaged emissivity and absorption coefficient are given by \( \epsilon_{\text{sync}} = 2450 (B/\text{Gauss})^{7/2} (\nu/\text{GHz})^{-1/2} \text{cm}^{-2} \text{Jy/cm ster} \) and \( \kappa_{\text{sync}} = 2.25 \times 10^{-12} (B/\text{Gauss})^4 (\nu/\text{GHz})^{-3} \text{cm}^{-1} \) respectively. At a given frequency the jet will become optically thin and thus visible for a comoving observer at a jet position \( z_{\nu = 1} \) where the optical depth along the line of sight, inclined by the angle \( \phi \) to the jet axis, is unity. For a ray right through the central axis of the jet and \( \phi \gg \phi \) we can approximate this by \( 2 \sin \phi z_{\nu = 1} = \kappa_{\text{sync}}(z_{\nu = 1})^{-1} \sin \phi \approx 1 \) neglecting the gradient in the magnetic field along the line of sight for \( \phi \neq \pi/2 \). To obtain the total flux at this frequency we then have to integrate the jet emission from \( z_{\nu = 1} \) to infinity (or whatever one considers to be the outer edge of the jet) yielding a flat spectrum. Transforming the equation into the observer’s frame, we have for the continuous, optically thin part of a jet (Lind & Blandford 1985)

\[
D = \frac{1}{\gamma_j}(1 - \beta_j \cos i_{\text{obs}}), \quad F_{\text{obs}}(\nu_{\text{obs}}) = D^2 F_{\text{obs}}(D\nu)
\]

\[
\nu = \nu_{\text{obs}}/D, \quad \sin i = D \sin i_{\text{obs}}, \quad \phi = \phi_{\text{obs}} \sin i_{\text{obs}}
\]

and obtain as the observed flux from one jet cone

\[
F_{\text{obs},1|2}(\nu_{\text{obs}}) = 1 \text{ Jy} \cdot D^{13/6} \sin i^{1/6} \left( \frac{M}{3} \right)^{-11/6} \left( \frac{\Lambda}{9} \right)^{-5/6} 
\]

\[
\left( \gamma_j \right)^3 \frac{q_m}{3\epsilon_{\text{sync}}} \frac{M_{\text{disk}}}{10^{-7} M_\odot \text{yr}} \right)^{17/12} \]

which is the original Blandford & Königl equation only with a new parametrization and the assumption that the opening angle of the jet is given by the Mach angle. We adopted a Galactic Center distance of \( D = 8.5 \text{kpc} \) and a central accretion rate of \( M_{\text{disk}} = 8 \times 10^{-7} M_\odot \text{yr}^{-1} \). The total flux from both cones is \( F_{\text{obs}} = F_{\text{obs},1|2} + F_{\text{obs},2|1} \).

2.5. Size of the emitting region

To find out whether the central core of the jet can be resolved, we transform the source size in the rest frame given approximately by \( z_{\nu = 1} \) into the observed size \( z_{\nu = 1, \text{obs}} \) which is
Fig. 1. The shaded area limits the parameter space for a coupled jet-disk system in Sgr A* producing a flat radio spectrum with $F_{\text{total}} = 1.1 Jy$ and a NIR-UV disk luminosity $\lesssim 5 \times 10^7 L_\odot$. The vertical axis gives the log of the total power extracted by the jet from the accretion disk normalized by the total accretion power $Q_{\text{accr}} = M_{\text{disk}} c^2$; for comparison: the radiative power of the accretion disk is $0.05 - 0.3 Q_{\text{accr}}$. The horizontal axis gives the log of the relative mass loss due to the jet compared to the mass accretion rate of the disk. Strongly bended lines in the plot represent models of equal Mach number $M$ whereas the less bended lines represent models of constant proper jet velocity $\gamma_{\text{jet}} \beta_{\text{jet}}$. The left figure is plotted for a jet seen side on with inclination angle $i = 90^\circ$, while the figure on the right is plotted for a jet with an axis inclined to the line of sight by $30^\circ$. A shift of the parameter grid with different accretion rates is indicated by text boxes and the shape of the shifted bounding lines of the parameter grid.

$$z_{\text{r}_\text{e}=1,\text{obs}} = 2 \times 10^{13} \text{ cm} \left( \frac{43 \text{ GHz}}{\nu} \right) \cdot \left( \frac{\gamma_{\text{jet}} \beta_{\text{jet}}}{1 + (\gamma_{\text{jet}} \beta_{\text{jet}})^2} \right)^{2/3} \frac{9}{\Lambda M} \frac{q_{\text{m}}}{3\%} \frac{M_{\text{disk}}}{10^{-7} M_\odot/\text{yr}} \left( \frac{\gamma_{\text{jet}} \beta_{\text{jet}}}{1 + (\gamma_{\text{jet}} \beta_{\text{jet}})^2} \right)^{2/3}.$$ \hfill (7)

We see that even at high frequencies the size of the jet is smaller than current VLBI resolution. If we go even further, i.e. to submm wavelengths, the size of the emitting region approaches the minimal size, which is the size of a Black Hole of mass $\sim 10^6 M_\odot$. This scale then should correspond to the ‘nozzle’ of the jet, producing the highest frequencies and fluxes and explaining the steep rise of the spectrum in the submm range (Zylka et al. 1992) as a self-absorbed, very compact and thus variable synchrotron source at the footpoint of the jet (and not as thermal dust emission). At higher frequencies (IR) non-thermal jet emission should not be detectable because of the large size of the Black Hole (Falcke & Biermann 1993).

2.6. Parameter space of jet-disk models

Now we can limit the parameter space for possible models of the jet-disk system in the Galactic Center. We know from observation that the flux from Sgr A* at 43 GHz is $F_{\text{43 GHz}} \approx 1.1 Jy$ (Krichbaum et al. 1993). Inserting this into equation (4) we get an equation for the relative mass loss $q_{\text{m}}$ in Sgr A* as a function of the opening angle, the velocity, the inclination angle and the Mach number of the jet. With $q_{\text{m}}$ specified, we can calculate the energy consumption $q_{\text{e}}$ of the jet relative to the disk from the energy equation (4). As a free jet should have an opening angle $\sin \phi \gtrsim 1/M$ and the radiative efficiency of the jet decreases with increasing opening angle the equality $\sin \phi = 1/M$ used in Eq. (4) gives a lower limit for the energy demand $q_{\text{e}}$ of the Sgr A* jet. Moreover we are not free to choose the other parameters completely arbitrarily. For a free jet the Mach number should be greater than one and as stated above for a given Mach number the jet velocity can not exceed $\gamma_{\text{jet}} \beta_{\text{jet}} \max = M \sqrt{\Gamma - 1}$. Because of mass conservation in the jet-disk system we have $q_{\text{m}} < 1$ and from energy conservation we get the limit $q_{\text{e}} < 1$. The latter is probably too generous, as there is at least some energy loss through the disk radiation and could be reduced to $2/3$ or even $1/3$ — the maximum efficiency of the disk.

Lastly, we need to specify the accretion rate of Sgr A*. Falcke et al. (1993) deduced a range of $10^{-7} M_\odot/\text{yr} > \dot{M} > 10^{-8.5} M_\odot/\text{yr}$ from standard accretion disk models and IR/NIR luminosities. The upper limit is obtained by assuming that most of the disk luminosity is absorbed in the surrounding dust and thus the disk luminosity can not exceed the dust luminosity. But as the dust is probably also heated by stars of the central cluster, the real disk luminosity will be much lower. On the other hand these models did not include the influence of a jet on the disk structure and efficiency. This may change the estimate of the accretion rate if $q_{\text{e}}$ is comparable to the radiative efficiency of the disk $q_{\text{e}}$.

3. Results

In Figure 1 we have plotted the lower limit of the relative energy demand $q_{\text{e}}$ and the relative mass loss rate $q_{\text{m}}$ of the Sgr A* jet compared to the accretion power and mass accretion rate of the disk as functions of the jet velocity and Mach number for two inclination angles and different accretion rates. The shaded area limits the possible parameter space for a Sgr A* jet-disk system being capable to produce 1.1 Jy radio emission. For our calculations we took as adiabatic index $\Gamma = 4/3$ and a fairly low logarithmic factor $\Lambda = 9$ which corresponds to a ratio of $\gamma_{\text{max}} / \gamma_{\text{min}} \sim 10^4$. These values are completely arbitrary, but a higher $\Lambda$ would again reduce the radiative efficiency, increase the energy demand and thus strengthen our conclusion. Note that the models with extremely low Mach number $M \lesssim 3$ re-
quire unrealistic large opening angles and the lowest part of the parameter grid is only plotted for completeness.

One can see that even for the highest disk accretion rates allowed by the IR dust observations the minimum energy requirements for a Blandford & Königl type jet are at least several per cent of the total accreted rest mass energy \( q_i > 2\% \). If one compares this with the radiative disk efficiency \( q_i \sim 5\% - 30\% \) one can say that within this model the Sgr A* jet could extract as much energy from the disk – in form of kinetic and magnetic energy – as is radiated by dissipative processes in the disk itself.

The minimum energy demands for the Sgr A* jet are found for low Mach numbers – this means high magnetic energy compared to the kinetic energy – and moderate relativistic velocities with \( \gamma \beta_1 \sim 0.1 - 6 \). The Mach number is limited to \( M < 40 \). Higher \( \gamma \)-factors or nonrelativistic velocities seem to be excluded. This is well within the range of parameters which is found in extragalactic jets.

On the other hand our analysis also gives a strict lower limit for the Sgr A* accretion rate namely \( M > 10^{-8.5} \frac{M_0}{\text{yr}} \) which is independent of the disk luminosity. Any lower accretion rates are not capable of producing such a strong radio emission. This agrees well with the lower limit given by Falcke et al. (1993) deduced earlier. And finally it should be noted that if one accepts the high energy extraction efficiency of the jet – despite our ignorance of the exact physical process being responsible for this – there is ample space in the parameter space left to positively state that the radio spectrum of Sgr A* can be understood as emission from a radio jet which is barely resolved due to a small spatial scale and a small power, both limited by the low disk accretion rate.

4. Discussion

Together with the spectra discussed in preceding papers (Zylka et al. 1992, Falcke et al. 1993) we can explain the spectrum of Sgr A* from radio to NIR in a consistent manner, including the flat radio spectrum (jet), the upturn in the submm range (‘nozzle’), the break in the IR (Black Hole) and a new component in the NIR (disk). It shows that such an AGN like scenario with Black Hole, accretion disk and jet may explain the inner part of the Galactic Center as well, but on a much lower level of activity. This is caused by a very low central accretion rate in the range \( 10^{-7} \frac{M_0}{\text{yr}} > M > 10^{-8.5} \frac{M_0}{\text{yr}} \) making the Galactic Center an AGN on a starvation diet.

The elongated structure found by Krichbaum et al. (1993) on the mas scale is well explained as a weak radio jet. On the kpc scale Sofue et al. (1989) found a large structure (‘Galactic Center Spur’) pointing at the Galactic Center which could well be the final smoke trail of our Galactic Center jet.

Our finding that the energy extracted by the jet in Sgr A* is comparable to the energy radiated by the accretion disk is not unique, Rawlings & Saunders (1991) came to a similar conclusions from a purely observational analysis of jet and disk emission of a large variety of radio galaxies. What is striking here, is that these radio galaxies are usually steep-spectrum radio sources associated with an active galactic nucleus inside elliptical galaxies. If indeed an ordinary spiral like our Milky Way shows a similar \( Q_{\text{jet}}/L_{\text{disk}} \) ratio as these AGN, then the ratio of jet power to disk luminosity is a consequence of fundamental jet-disk physics and not special to any type of galaxy, whereas the absolute powers of jets and disks are a consequence of different host galaxies, i.e. the different processes of feeding. Interestingly our equation predicts a certain scaling of radio emission from the central radio core with accretion rate which should hold for AGN as well.

The combined jet-disk system we have sketched here, is of course very simplified, but as we have concentrated on the basic energetics this seems to be justified. Moreover, the statement that the jet extracts a non negligible part of the accretion power is fairly robust, as we always used lower limits for the energy demand of the jet.

Nevertheless, some assumptions of the Blandford & Königl model may be violated but only a few of them making a lower \( Q_{\text{jet}}/L_{\text{disk}} \) possible. For example the jet could be additionally confined with an opening angle smaller than the Mach angle, and therefore be more efficient. Perhaps with better data at hand (e.g. velocity and opening angle of the jet or the mass accretion rate) such an additional confinement may even be required to explain the high efficiency of the Sgr A* radio jet compared to the luminosity of the accretion disk. On the other hand, the jet could extract additional rotational energy from the Black Hole (Blandford & Znajek 1977) or reduce the disk luminosity by its influence on the accretion process, which we have not included in our model. There are also spherical accretion scenarios (Melia et al. 1992) which, however, seem to be disproven by the observation of a non-spherical structure. Finally there could be a less efficient central object – other than a Black Hole – or a not fully dissipative disk changing the estimates for the accretion rate.

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