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Disks with Jet, ADAF, or EDAF for Sgr A*

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Abstract. We investigate various models of accretion disks for Sgr A*, one of the most puzzling sources in the Galaxy. The generic image we have taken into account consists of a black hole, an accretion disk, and a jet. Various accretion models are able to explain the low NIR flux of Sgr A*: a standard accretion disk with a jet, an ADAF, or an EDAF (Ejection Dominated Accretion Flow) model. We find that all of these models are conceptually similar. The accretion model which allows the formation of the jet at the innermost edge of the disk requires a sub-keplerian gas motion and a very large base of the jet. The large base of the jet may be unrealistic for Sgr A*, since the jet model and the observations suggest that the jet is collimated and anchored in the disk in a very narrow region of the disk close to the black hole. Alternatively, one can think of a jet plus wind model (EDAF), where most of the energy goes out without being dissipated in the disk. The model resembles the ADAF model at small radii. At large radii the energy is ejected by a wind.

1. Introduction

As it is well known the Galactic Center harbors a black hole candidate of $(2.5 \pm 0.4) \cdot 10^6 M_\odot$ mass (Eckart & Genzel 1997). The accretion rate inferred from Bondi-Hoyle accretion of stellar winds should be small and should be of order $10^{-4}\dot{M}_\odot$ (Genzel et al. 1994, Melia 1992), but the exact number will depend critically on the distribution of stellar wind sources in the Galactic Center (Coker & Melia 1999). What is peculiar about the central part of our Galaxy is that, for a radiative efficiency of 10% of the accretion flow, the accretion luminosity should be higher than 10^{40} erg/s. This directly contradicts the bolometric luminosity of $\sim 10^{37}$ erg/s inferred from observations. This means that a standard accretion disk does not work. To have such a low luminosity the accretion disk in Sgr A* has to be radiatively deficient.

There are several accretion models which in principle can produce such low luminosities: ADAF (advection dominated accretion flow) models (Narayan, Yi & Mahadevan 1995, Narayan & Yi 1994), disks driving jets from the innermost regions (Donea & Biermann, 1996) or an EDAF (ejection dominated accretion flow) model (see below). All models provide a low luminosity which can explain the data of Sgr A*.

As it has been emphasized by Falcke & Biermann (1995, 1999) a symbiosis between the accretion disk, jet, and the central black hole has become a widely accepted model for active galactic nuclei and recently also for some of the micro-quasars. The strong radio emission in these systems comes from relativistic jets emitting synchrotron radiation. Based on the jet–disk symbiosis, Falcke (1999) has explained the radio emission in Sgr A* as being due to a radio jet. The model fits well all current radio observations. In the following we will make use of this model and the jet-disk symbiosis idea to calculate a number of accretion disk models that would be consistent with the observed properties and upper limits of Sgr A*.

2. Accretion Disk with Jet

Donea & Biermann (1996) have put forward an accretion disk model with a jet starting at the inner regions of a disk. The jet extracts energy, mass and angular momentum from small radii of the disk. They have written the conservation laws of mass and angular momentum taking into account the extraction of mass, angular momentum and energy by the jet (Newtonian treatment). The new conservation mass law is:

$$\dot{M} = -2\pi R \Sigma u^R + \dot{M}_{jet} \tag{1}$$

where $\dot{M}$ is the rate of mass accretion rate in the disk. The mass flow rate into the jet is $\dot{M}_{jet}$. The angular momentum conservation law is:

$$2\pi R \Sigma v_R(R)\ R^2\Omega = 2\pi R \nu \Sigma R^2 \Omega' + \dot{M}_{jet} v_\phi(R_{jet}) R_{jet} + C \tag{2}$$

ν is the kinematic viscosity of the disk. R_{jet} is the radius where the base of the jet starts. The constant C is related to the boundary conditions of the accretion flow (Frank et al. 1985).

We assume that the jet starts between $R_{\rm ms}$, the last marginally stable orbit in the absence of a jet and the radius $R_{\rm jet}$ with $R_{\rm jet} > R_{\rm ms}$. (Donea & Biermann 1996). The presence of the jet will modify both the behaviour of the infalling matter across the radius $R_{\rm jet}$ and the structure of the relativistic disk.

The local energy dissipation in the disk becomes:

$$D^*(R) = \frac{3GM\dot{M}}{8\pi R^3}\left[(1-q_m) - (1-q_m)\left(\frac{R_{jet}}{R}\right)^{1/2}\right] \tag{3}$$

where

$$q_m = \frac{\dot{M}_{jet}}{\dot{M}}, \tag{4}$$

As we mentioned before, the gravitational potential energy released between $R_{\rm ms}$ and the outer radius of the jet, $R_{\rm jet}$ goes into the jet. Therefore, the total energy carried outwards by the jet is strongly dependent on the mass and angular momentum of the black hole. Q_{jet} is the total power of the jet – including the rest mass energy of the expelled matter – and is expressed as:

$$Q_{jet} = L_{disk} - L_{disk}^{jet}$$

L_{disk}^{jet} is the total luminosity of a disk modified by the presence of the jet and L_{disk} is the total luminosity of the disk if there are no physical conditions to drive the jet.

The power of the jet depends on the the way in which the jet gets energy from the black hole/disk system. Total power of the jet and the radio activity of the AGN are probably directly connected to the inner geometry of the system near the event horizon. Adopting the point of view that formation of jets is possible under all circumstances (Falcke & Biermann 1995), be it for an AGN or a stellar size system, we investigate the effects of the presence of the jet on the structure of the accretion disk, and implicitly on its emission spectrum.

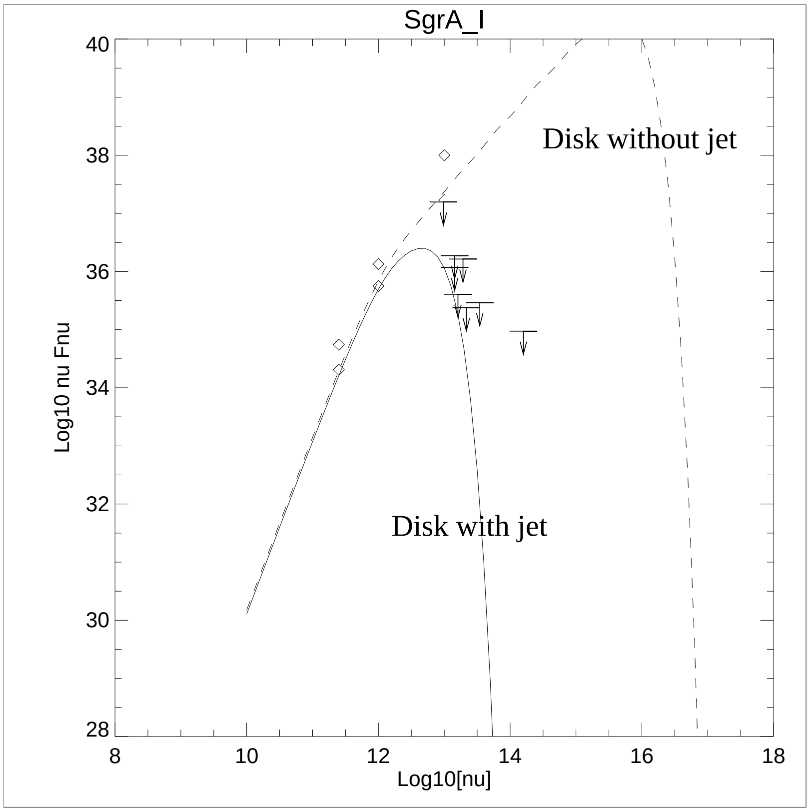

Figure 1. The emission from an accretion disk with a jet starting at large radii in the disk. $M = 2.5 \cdot 10^6 M_\odot$; Kerr black hole: $a_\star = 0.9982$; $\dot{M} = 2 \cdot 10^{-6} M_\odot/yr$; fitting the data below the NIR requires an extremelysh large base of the jet.

We applied the above disk–jet model to the case of Sgr A*. The spectrum from the disk is below the NIR flux if one considers the emission from a thin disk surrounding a Kerr black hole of $2.5 \pm 0.4 \cdot 10^6 M_\odot$. In Figure 1 we show a spectrum from a disk with jet (the dashed line) and without the jet (continuous line). As it is expected from the standard models (Shakura & Sunyaev (1973), Novikov & Thorne 1973) the standard model does not fit data at all. If one takes into account the jet, then the model is completely different: the high energy part of the spectrum is cut off due to the extraction of energy by the jet from small radii.

The parameters of the model (see Figure) are :

– low accretion rate: $\dot{M} = 2 \cdot 10^{-6} M_{\odot}/yr$.

– black hole mass: $2.5 \cdot 10^{6} M_{\odot}$.

– Kerr black hole: $a_{\star} = 0.9982$.

Interestingly, the NIR limits are now so stringent that fitting the data with such a model would require an extremely large base of the jet, from $1.23 R_{\rm g}$ to $7000 R_{\rm g}$. The outer radius of the disk is $2 \cdot 10^{5} R_{\rm g}$. The luminosity of the disk is $L_{\rm disk} = 3.7 \cdot 10^{36}$ erg/s and Q_{jet} takes out 99.5% of the total gravitational energy.

This is not a realistic situation for Sgr A*, since we know that the radio emission is much more concentrated. Nevertheless, these results point into two very interesting directions for modifying accretion disk theory. For one, the disk model with large fraction of energy extraction resembles an ADAF model (Narayan & Yi, 1994) in various points:

a) the region between the radius of the last marginally stable circular orbit R_{ms} and the radius where we consider to be the outer radius of the jet R_{jet} no longer shows a standard disk-like structure;

b) the flow becomes subkeplerian in the region where the jet is formed;

c) at these radii there is no radiative cooling any more of the flow—the energy is advected in a jet instead of being radiated away.

3. The Ejection Dominated Accretion Flow

A second way to think of our results, is that for such a large region where energy extraction is required one can hardly speak of a 'jet' any more. Rather, one could think of a continuous process, where a magnetically driven wind across the accretion disk would extract a large fraction of the dissipated energy. The jet would then only be the most highly collimated and fastest feature in such a wind.

Like in the ADAF model, the energy of the disk would no be radiated away, but advected away. Unlike the ADAF model, however, the channel through which the energy is advected would no longer be the disk, but rather the wind. In light of these connections with the existing ADAF theory we have labeled our approach EDAF—ejection dominated accretion flow.

Indeed, the fact that accretion disks are able to expel a large fraction by, most likely magnetically driven, jets opens up the possibility that a related process could also drive large scale winds from an accretion disk. Since it is often suggested that the viscosity and dissipation in accretion disks is also a result of magnetic fields, a deeper connection between viscosity, dissipation, and wind ejection may exist. In cases where wind ejection dominates the energy dissipation, a substantial part of the accretion energy could be extracted by the wind from the accretion disk. In this case the large radius of $7000R_{\rm g}$ we obtained earlier may be the radius where a significant wind coexists with the disk (EDAF models). As pointed out in Falcke (1999) application of the jet model indeed supports a non-standard, radiatively deficient accretion disk in Sgr A*. The EDAF model would be a situation where the wind goes off from the accretion disk at every radius and where at each radius a fraction of the available energy is put into a wind.

Falcke & Melia (1997) solved the accretion disk equation for the case of deposition of mass and angular momentum onto the disk by an infalling wind. The reverse case, when the wind takes out mass and angular momentum, would be an EDAF case. The equations remain the same, only the sign of the mass loss/gain rate $\dot{\Sigma}_{\rm w}$ at each radius changes.

We have used the code described in Falcke & Melia (1997) to simulate such a situation. The important parameter for these calculations is the energy extraction efficiency: we assume that at each radius a fraction $f_{\rm EDAF}$ of the locally dissipated energy is put into kinetic and internal energy of the wind. The wind is assumed to leave the disk with escape speed and with the specific angular momentum and internal energy corresponding to the local conditions in the disk. The local mass loss rate $\dot{\Sigma}_{\rm w}(r)$ is then completely determined by $f_{\rm EDAF}$.

To facilitate the connection to the jet model we also assumed that the wind extraction efficiency approaches unity at the inner $12R_{\rm g}$, i.e. all the energy is used to drive the jet modeled in Falcke (1999). Because of the continuous mass loss throughout the disk, the accretion rate at small radii and the available energy is significantly reduced with respect to a standard disk model. Moreover, the emitted radiation spectrum will also look markedly different (i.e. flatter) from a standard $\alpha-$disk.

The F_ν emission spectrum from an EDAF we have calculated for the situation in Sgr A* is shown in Figure 2. The bump at low frequencies is due to heating of the disk by the surrounding stars, which we had to take into account as well. The spectrum lies below the NIR limits. In Figure 2 the radio spectrum from the jet assumed to be produced at the innermost radii by the remaining accretion flow is also shown. The great disadvantage of such a model is that $f_{\rm EDAF} = 99.995\%$ of the locally produced energy has to go into a wind rather than into heat for an initial accretion rate of $\dot{M} = 10^{-6} M_\odot/{\rm yr}$. Even though we do not have any arguments for how large the value of $f_{\rm EDAF}$ really has to be, this seems uncomfortably high. On the other hand this high 'inefficiency factor' is very similar to those required for ADAF models. In both cases one wonders whether such values are physically meaningful. Perhaps various combinations of the models explored here (e.g. ADAF+EDAF) could lead to a more convincing solution to the inefficiency problem, or the mass accretion rate on Sgr A* is significantly lower than the already low value used in our calculations.

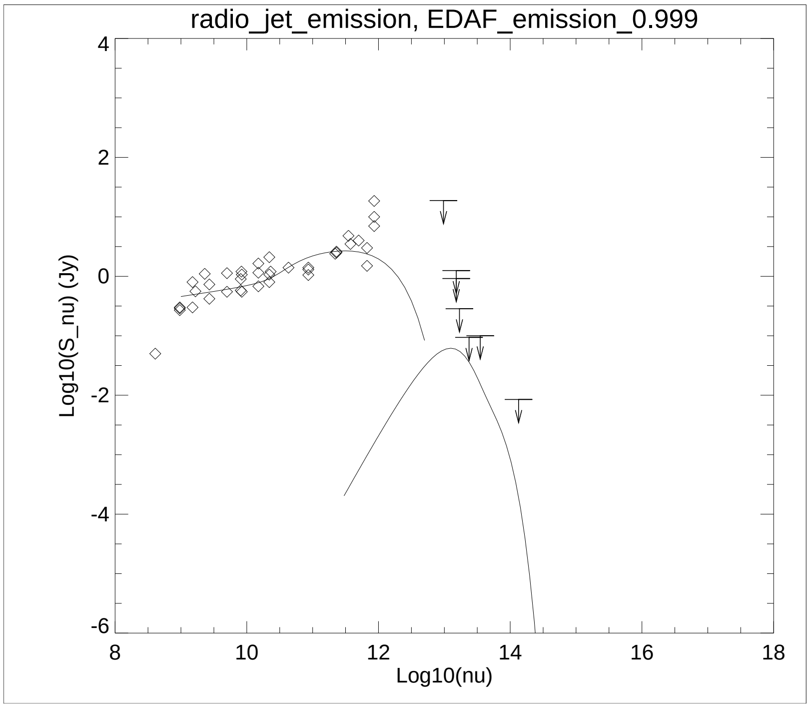

Figure 2. The radio emission and the spectrum from an EDAF (Ejection Dominated Accretion Flow) model of Sgr A*.

4. Conclusions

We conclude that there are in principle various ways to explain the low NIR flux and that all the models (jet, EDAF, ADAF) are conceptually very similar. However, each of these models seems to require rather extreme parameters to explain the inefficiency of the accretion flows.

The basic picture for the very central part of our Galaxy, explored here, consists of an accretion disk, a black hole and a jet. The accretion disk may be an EDAF or a "standard" disk at large radii. The angular momentum and part of the dissipated energy goes out with the wind. Perhaps at small radii, the disk becomes an ADAF with a jet. The jet–disk model allows the formation of an jet at the innermost radii and this would automatically produce a subkeplerian, disipationless flow similar to an ADAF. In any case a large fraction of the energy produced in the accretion disk in Sgr A* has to be either advected into the black hole or ejected by a wind or jet.

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