A rotating black hole in the Galactic Center

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Abstract

Recent observations of Sgr A* give strong constraints for possible models of the physical nature of Sgr A* and suggest the presence of a massive black hole with $M \leq 2 \cdot 10^6 M_\odot$ surrounded by an accretion disk which we estimate to radiate at a luminosity of $< 7 \cdot 10^5 L_\odot$. We therefore calculate the appearance of a standard accretion disk around a Kerr hole in Sgr A* following from general relativity and a few fundamental assumptions. Effective temperature and luminosity of the disk spectra do not depend on the unknown viscosity mechanism but instead are quite sensitive to variations of intrinsic parameters: the mass, the accretion rate, the angular momentum of the accreting hole and the inclination angle.

A radiation field of $L \simeq 7 \cdot 10^4 - 7 \cdot 10^5 L_\odot$ and $T_{\text{eff}} \simeq 2 - 4 \cdot 10^4 K$ can be ascribed to a rapidly rotating Kerr hole ($a > 0.9$) accreting $10^{-8.5} M_\odot/\text{yr} < \dot{M} < 10^{-7} M_\odot/\text{yr}$ at a black hole mass of $M \leq 2 \cdot 10^6 M_\odot$ seen almost edge on. A low mass black hole of $M \leq 10^3 M_\odot$ seems to be very unlikely.

Due to the large uncertainties in the observational determination of the effective temperature further observations are required. Therefore we provide a “Hertzsprung-Russell diagram for black holes” together with simple scaling laws to provide a test for the black hole/accretion disk scenario in the Galactic Center and give a direct method to measure such intrinsic parameters as the angular momentum and the accretion rate of the hole.

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1 Introduction

There is mounting evidence for the presence of a black hole surrounded by an accretion disk at the center of our Galaxy, provided by the following observations:

i) The kinematics of gas and stars in the inner parsecs requires an enclosed mass of a few $10^6 M_\odot$ within a galacto-centric radius of $R \leq 0.1$ pc (see Genzel & Townes 1987, Sellgren 1988 and references therein).

ii) Morphology and kinematics of the layer of interstellar matter between the inner Lindblad resonance (i.e. $R \leq 2.5$ pc) and $R \simeq 1 – 0.1$ pc show the expected characteristics of accretion disks in Active Galactic Nuclei (AGN) (Zylka, Mezger & Lesch 1992 (hereafter ZML92), and references therein).

iii) Close to, or at the dynamical center of the Galaxy is the variable radio source Sgr A* interpreted as synchrotron emission. Its mm/submm and FIR spectrum is best explained by $\simeq 30 – 60$K dust emission from an irradiated accretion disk (ZML92) which extends to $10^{17}$ cm and contains a mass of $400 – 800 M_\odot$.

iv) The luminosity of the compact central object is $L \leq 7 \cdot 10^5 L_\odot$, far below the Eddington limit of $\simeq 2 – 4 \cdot 10^{10} L_\odot$ for a black hole with $M \simeq 1 – 2 \cdot 10^6 M_\odot$. A cavity in the Sgr A East core could be due to an explosive event in the past, when this accretion rate was several magnitudes higher (Zylka et al 1990).

v) The radio emission of Sgr A* could be explained as emission from a small scale nuclear jet, stressing the analogy to AGN (Falcke, Mannheim & Biermann 1992) where a massive black hole with an accretion disk is still the best explanation for the central engine. 7 mm (Krichbaum et al. 1992) and 3 mm VLBI observations of Sgr A* – currently being evaluated or prepared – will therefore give a firm test for the whole scenario.

Hence if there is a black hole surrounded by a hot accretion disk in the center of the Galaxy it would be underfed at present with an accretion rate of $\dot{M} \ll 10^{-6} M_\odot/yr$ as compared with an accretion rate of $\simeq 0.03 M_\odot/yr$ in the Eddington limit. The luminosity of $\leq 7 \cdot 10^5 L_\odot$ of the starved black hole would be mainly contributed by thermal free-free emission from a $T_e \simeq 2 – 4 \cdot 10^4$K plasma at the inner edge of an accretion disk (ZML92) in agreement with recent NIR observations by Eckart et al. (1992).

Various other attempts fail to explain these features of Sgr A*. Therefore in this paper we propose to test the black hole concept in more detail by calculating the appearance of a disk around a rotating black hole, considering specifically the effects of the Kerr metric on the spectrum. We will demonstrate that a
black hole mass of about $2 \cdot 10^6 \, M_\odot$ and the radiation field described above require a strongly rotating Kerr black hole with a low accretion rate and seen almost edge on.

However, at the moment the observational basis is too weak to give an unambiguous answer to the question whether such a configuration exists in the Galactic Center, since most of these observations are at the limit of what is technically possible. For an observer it should therefore be of highest interest to know, which the crucial observations are for a confirmation of a black hole/accretion disk configuration and for a determination of its parameters. We therefore compute in this paper the characteristics of such a configuration for a parameter range suggested by the observations above. We find that a refined measurement of the effective temperature and the luminosity of the central object together with our grid of parameters should make it possible to differentiate between parameter combinations for a black hole/accretion disk model of the Galactic Center and even gives an estimate for the angular momentum of the hole.

2 A critical review of the crucial observations

The crucial observations related to the nature of the central compact object and its surrounding disk are: the kinematics of gas and stars, the mm-to-MIR spectrum of the central arcseconds, the NIR spectrum of Sgr A* and its effective temperature and luminosity.

Genzel & Townes (1987) and Sellgren (1988) – based on the same observational results – arrive at somewhat contradictory interpretations. Genzel & Townes state that the data are best approximated by a star cluster and a central point mass of $\simeq 2.5 - 3 \cdot 10^6 \, M_\odot$. Sellgren states that – if the core-radius of the star cluster is $\leq 0.1 \, \text{pc}$ – no central point mass is required, although in our opinion the model fit shown in her Fig. 4 requires a point mass of the order of $\sim 10^6 \, M_\odot$.

The interpretation of the mm-to-MIR spectrum in terms of dust emission (ZML92) from a compact cloud of $\simeq 1 \, \text{arcsec}$ diameter could in principle be strengthened by interferometric observations at $1 \, \text{mm}$ and by additional flux density measurements in the $\lambda 460 \, \mu \text{m}$ and $\lambda 350 \, \mu \text{m}$ windows. These observations have been made but are not yet evaluated.

How well are the effective temperature and luminosity of the central object known? The dereddened spectrum (Eckart et al. (1991) adopt $A_K = 3.4$ and $A_H = 5.4$ corresponding to $A_v = 27 \, \text{mag}$) can be approximated by a Rayleigh-Jeans spectrum. Hence, if the radiation is thermal free-free emission from an opaque plasma, its electron temperature must be $T_e > 10^4 \, \text{K}$. This sets a lower limit for both $T_e$ and $L$. Combining the Rayleigh-Jeans approximation $S_{\text{NIR}} \propto \Omega_s T_e$ ($\Omega_s$ is the source solid angle) with the integrated Planck spectrum
$$L \propto \Omega_s T_e^4$$ yields

$$L = 7.5 \cdot 10^4 (T_e/20000K)^3 L_\odot.$$  \hspace{1cm} (1)$$

ZML92 obtained the luminosity of the central 30” by integrating the observed spectrum

$$L_{IR}(30”; \lambda \geq 10 \mu m) = L_{IR}(\text{star cluster}) + L_{IR}(\text{central object}) \simeq 1.5 \cdot 10^6 L_\odot$$ \hspace{1cm} (2)$$

This assumes that heating of the dust is due to contributions from both the star cluster and a central object. The contribution from the star cluster can be estimated from IRAS observations (Cox & Laureijs 1989). Fig. 14 of Cox & Mezger (1989) shows the accumulated bolometric luminosities of the star cluster (derived by Sanders and Lowinger (1972) from the A2.2µm surface brightness) and IRAS. Within $10 \leq R_{pc} \leq 200$ both have the same functional dependence $L \propto R_{pc}^{1.2}$. Specifically, the accumulated IRAS dust luminosity is

$$L_{IRAS}(R) = 1.5 \cdot 10^6 R_{pc}^{1.2} L_\odot$$ \hspace{1cm} (3)$$

yielding $L_{IR}(30”; \text{star cluster, } \lambda \geq 10 \mu m) \simeq 8 \cdot 10^5 L_\odot$ and leading to $L_{IR}(\text{central object}) \simeq 7 \cdot 10^5 L_\odot$.

On the assumption that all radiation from the inner disk is absorbed by dust in the central 30” we can substitute the above luminosity in Eq. (1) and obtain an electron temperature $T_e \simeq 42000K$. This is an upper limit since all other effects – e.g. a substantial contribution of the “He I emission-line stars” detected by Krabbe et al. (1991) in the inner parsec or a probable increase of dust extinction beyond $A_v = 27$ mag – tend to decrease $T_e$ but increase $L$ for a given $T_e$. Thus

$$20000K < T_e < 42000K$$ \hspace{1cm} (4)$$

and

$$7 \cdot 10^4 L_\odot < L(\text{central object}) < 7 \cdot 10^5 L_\odot$$ \hspace{1cm} (5)$$

seem to be reasonable limits for $T_e$ and $L$ of the central object.

Although our estimate of the effective temperature falls exactly in the regime derived before from the ionization state of gas in the inner 3 pc (Genzel & Townes 1987, Sect. 3, Roberts et al. 1991) it is doubtful whether one can use these estimates as observational parameters to fit accretion disk models to the central object. Firstly, one should expect that with such low luminosities the ionization of the gas is dominated mainly by hot stars in the central star cluster (Krabbe et al. 1991) and secondly, because the spectrum of an accretion disk – being a superposition of black body spectra – is usually flatter than $S_\nu \propto \nu^2$.\footnote{This is the relation given by Eckart et al. (1991) for a disk distribution of the surface brightness which is more likely than the gaussian distribution adopted by ZML92, yielding $L = 2 \cdot 10^5 T_e^{\frac{3}{2}} L_\odot$.}
Only for high inclination angles, nearly edge on, the disk spectrum comes close to a black body type. The fit of a one-component Planck function to a flatter spectrum thus can lead to an underestimate of the actual effective temperature of the inner edge of the disk. The uncertainties in the observations still allow a broader range of spectral indices.

3 The signature of rotating black holes

Fortunately the main results for standard accretion disks theory (von Weizsäcker [?], Shakura & Sunyaev [?]) and its general relativistic extension (Novikov & Thorne [?]) follow from fundamental physics with only a few assumptions:

- The gravitational field is dominated by the central black hole and the metric is described by a Kerr metric (Kerr [?]) allowing for rotation of the black hole. Parameters of the metric are mass $M$ and Kerr parameter $0 \leq a \leq 1$ of the black hole ($a \propto$ angular momentum of black hole).

- Matter flows along direct, nearly circular, geodesic orbits in the equatorial plane of the black hole.

- Angular momentum is transported outwards due to a turbulent viscosity mechanism resulting in a radial velocity of the matter towards the center, which is much smaller than the circular velocity of the matter.

- The disk is thin (height < radius/3) and steady.

- At the inner edge of the disk, angular momentum, mass and energy of the inflowing matter are swallowed completely by the black hole.

Having such an accretion disk the amount of gravitational energy which has to be dissipated per surface area and time (dissipation rate $D_0$) at each radius can be calculated simply from conservation of energy and angular momentum, yielding

$$D_0 = \frac{3GM\dot{M}}{8\pi R^3 \frac{Q}{B\sqrt{C}}} = 6.8 \cdot 10^{37} \frac{\dot{m}_8}{\dot{m}_{-8}} \frac{Q}{B\sqrt{C}} \frac{\text{erg}}{s \frac{R_6^2}{R}}$$ (6)

which is independent of the viscosity parameter $\alpha$ defined by Shakura & Sunyaev (1973). Assuming black-body radiation this can be translated to an effective temperature via

$$T_{\text{eff}} = (D_0/\sigma)^{1/4}$$ (7)

which in turn defines a characteristic frequency

$$\nu_{\text{max}} = 8.2 \cdot 10^{10} \left(\frac{T_{\text{eff}}}{\text{K}}\right) \text{ Hz}$$ (8)
where the black-body radiation of this temperature has a maximum in $\nu F_\nu$:

$$\nu_{\text{max}} = 7 \cdot 10^{15} \frac{\dot{m}_{-8}}{m_6^{1/2} \left( \frac{1}{r_3 B \sqrt{C}} \right)^{1/4}} \text{Hz} \quad (9)$$

Here $m_6 = M/10^6 M_\odot$ and $\dot{m}_{-8} = \dot{M}/10^{-8} (M_\odot/\text{yr})$ are the dimensionless mass and accretion rate of the black hole. $r = R/R_g$ is the dimensionless radius in units of the gravitational radius $R_g = GM/c^2 = 1.48 \cdot 10^5 M/M_\odot \text{cm}$ which is half the Schwarzschild radius. The inner edge of an accretion disk lies at the radius $r_{\text{ms}}(a R_g)$ of the last, marginally stable orbit, which is $6 R_g$ for a nonrotating ($a = 0$) and $1.232 R_g$ for a maximal rotating black hole ($a = 0.9981$). The relativistic correction factors $B, C$ and $Q$ are functions of $r$ and $a$ with the limits such that $D_0 \propto r^{-3}$ for $r \to \infty$ and $D_0 \to 0$ for $r \to r_{\text{ms}}$. They are given explicitly in Page & Thorne (1973). Note that the dependence of the disk properties on the Kerr parameter $a$ is contained completely in these correction factors and in the marginally stable radius $r_{\text{ms}}$. For fast rotating black holes luminosity and effective temperature of the disk may be up to 5 times higher than in the non-rotating case mainly because the disk extends to lower radii. The radiation field of the disk is most sensitive to changes of the holes angular momentum in the regime $a > 0.9$. Because of this sensitivity one has for given black hole mass and inclination angle an unequivocal translation from the two observables effective temperature and luminosity ($T_{\text{eff}}, L$) to a new pair of intrinsic properties, namely angular momentum and accretion rate ($a, \dot{M}$) of the hole.

4 Inner boundary conditions for a Kerr accretion disk

Standard accretion disk theory assumes that at the inner boundary of the accretion disk the effective temperature goes to zero. In the stellar case a finite boundary layer has to exist which can produce an appreciable part of the total luminosity, and which may also encompass a non-negligible part of the accretion disk near the inner boundary (Duschl & Tscharnuter 1991). In the case of black hole accretion, one expects a similar phenomenon (Kato 1982). But as it is not necessary for the matter to slow down before being swallowed by the hole as in the stellar case we neglect all such effects and use the standard Novikov & Thorne (1973) boundary condition described at the beginning of Sect. 3. And even if there is a luminous boundary layer most of the emitted photons will not be able to escape from the very edge of the black hole – the relativistic transferfunction tends to zero (Cunningham 1975), however the radial structure of the disk may change in the inner part.
Figure 1: “Hertzsprung-Russell diagram for a black hole” of $2 \cdot 10^6 M_\odot$. Plotted is the effective temperature of the radiation flux (maximum in $\nu F_\nu$) for a disk seen almost face on ($\cos i = 0.9$) and a disk seen almost edge on ($\cos i = 0.05$) versus the total luminosity of the disk for a grid of angular momenta and accretion rates. The rectangle represents the observational constraints from Sgr A*.

The arrow indicates how the whole grid shifts if one divides the black hole mass by a factor of 2.

5 Radiation field in the Kerr metric

To build up a translation table from $(T_{\text{eff}}, L)$ to $(a, \dot{M})$ we used the method from Cunningham ([3]) to calculate the full general relativistic geodesic transformation of radiation in the Kerr-metric (i.e. gravitational redshift, boosting, light bending). We assumed that the disk radiates locally as a black-body with an additional limb-darkening law $I_\nu(\theta) = (1 + 1.5 \cos \theta)/1.75 \cdot B_\nu$. $B_\nu$ is the Planck function with $T_{\text{eff}}$ taken from Eqs. (6,7). In our scenario, where $M \sim 2 \cdot 10^6 M_\odot$ and $\dot{M} \ll 10^{-5} M_\odot/\text{yr}$, the standard theory predicts an accretion disk which is dominated entirely by gas pressure (Novikov & Thorne [4], Eqs. (5.9.6+8)) so that these assumptions are justified with the exception of a possible weak modification of the spectrum in the inner region of the disk due to electron scattering, which was neglected. But since we are mainly interested in the energetics of the disk radiation, we do not require elaborate disk spectra at this stage.

Using the more detailed accretion disk theory (Novikov & Thorne 1973) – including the viscosity parameter $\alpha$ – one finds that the disk is optically thick everywhere, for a low viscosity parameter $\alpha \leq 10^{-4}$ as used for the modeling of comparable disks for FU Orionis events (Hessman 1991, Clarke et al. 1990). Only at low accretion rates $\dot{m} \leq 10^{-8} M_\odot/\text{yr}$ and high $\alpha$, an intermediate part of the disk may become optically thin. However, this does not affect the outcome of our of the order estimates drastically, as the high and low temperature parts of the disk still remain optically thick. The results do also not depend crucially on the assumed limb-darkening law.

A variety of spectra were calculated as viewed by an observer at infinity from different inclination angles for a black hole with $M = 2 \cdot 10^6 M_\odot$, angular momentum ranging from $a = 0.1$ to $a = 0.9981$. Because of relativistic boosting the effective temperature of these spectra is maximal at high (edge on) and minimal at low (face on) inclination angles, whereas the apparent luminosity is lower at large and higher at low inclination angles. The temperature effect is much more pronounced in the case of rotating black holes while the luminosity effect is stronger for non-rotating holes.

From each spectrum we took the maximum in $\nu F_\nu$ and converted the corresponding frequency via Eq. (6) to an effective temperature. This corresponds
Figure

Figure 2: Sample spectra of an accretion disk around a Kerr hole (a=0.9981) together with the λ=2.2, 1.6 and 1μm data from Eckart et al., Close et al. (1992) and Rosa et al. (1991). The labels refer to different values of mass and accretion rate. Spectra a)-d): face on disk with $M = (2 \cdot 10^6, 2 \cdot 10^5, 2 \cdot 10^4, 2 \cdot 10^3)M_\odot$ and $\dot{M} = (10^{-10}, 10^{-9.5}, 10^{-8.5}, 10^{-7.5})M_\odot/yr$. Spectra e)-h): edge on disk with $M = (2 \cdot 10^6, 10^6, 10^5, 10^4, 10^3)M_\odot$ and $\dot{M} = (10^{-8.5}, 10^{-8}, 10^{-7.5}, 10^{-7})M_\odot/yr$. The total luminosity for a maximal Kerr hole is given by $L_{\text{tot}} = 2 \cdot 10^{38} \dot{m}_\odot$ erg/s.

to the effective temperature of the energetically dominant part of the disk – usually within a few gravitational radii from the black hole. The results are shown in Fig. 1 where we plotted these effective temperatures versus the $4\pi$ integrated flux (i.e. total luminosity) of the disk for a grid of angular momenta and accretion rates. Also shown are our observational constraints for the Galactic Center. Some selected spectra for different parameters are shown in Figure 2.

The spectral form of the disk radiation (exponential cut-off) ensures that – unless further hot components are present – the effective temperature is also very close to the high-energy cut-off for the overall photon spectrum. That is very important for the impact of the disk radiation on the ambient medium, i.e. ionization and heating. Different black hole/accretion disk models may lead to different temperatures in the surrounding gas due to photoionization. This diagnostic tool will be considered in more detail in a subsequent paper (Falcke et al. 1992).

We took a canonical black hole mass of $2 \cdot 10^6 M_\odot$ as our reference model but one can easily obtain a similar grid for different masses simply by using the Relations (6) and (9). As one can see the luminosity scales with $L = 2 \int_{r_{\min}}^{r_{\max}} D_0 2\pi dr \propto \dot{M}$ and is independent of the black hole mass $M$, while the effective temperature scales with $T_{\text{eff}} \propto \dot{M}^{1/4}/\sqrt{M}$. Thus one can obtain further models for different parameters of $M$ and $\dot{M}$ by simple linear extrapolation.

6 Discussion

If the observational constraints could be confirmed then Fig. 4 requires a fast rotating Kerr hole ($a > 0.9$) with a fairly low accretion rate of $\dot{M} < 10^{-7} M_\odot/yr$ seen almost edge on.

In fact if we fit the disk spectra directly to the NIR spectrum than an even lower accretion rate of $\dot{M} \sim 10^{-8.5} M_\odot/yr$ seems also possible (Fig. 5), giving also a lower limit, because an even lower accreting disk would not be capable of reproducing the NIR data. From this figure one can also see – like in the HR-
diagram – that a low mass black hole with $M \ll 10^6$ (e.g. $\sim 10M_\odot$ as proposed by Sanders (1992)) and an edge on disk fitted to this data would produce a luminosity, exceeding the limit from the dust observations, whereas the face on disk models produce spectra which are obviously too flat.

So if the central disk really is edge on, then it is suggestive to assume that it is also roughly aligned with the galactic plane, with the rotation axis perpendicular to it. This, however, cannot be confirmed by NIR observation, but has to await mm VLBI experiments to prove non-spherical structure in Sgr A* and thus to fix the orientation of the disk in the observer’s plane.

If the constraint on the mass of the putative black hole could be relaxed then a lower black hole mass could also fit into the Hertzsprung-Russell diagram, with no particular constraint on the Kerr parameter. But during the evolution process of a black hole it is quite natural to expect an evolution towards strong rotation to a maximum at $a \approx 0.9981$ (Bardeen [?], Thorne [?]). From Fig.2 one can see that a maximal Kerr Hole of $M = 10^6$ would then require at least $10^{-8}M_\odot/yr$.

Therefore the Galactic Center could become an important laboratory to study general relativity and the Kerr metric. This model gives some firm predictions:

- strong anisotropies of the effective temperature of the radiation field for a strongly rotating black hole resulting in an anisotropic ionization of the ambient medium, and
- strong anisotropies for the luminosity of the radiation field for non-rotating black holes.

The results are summarized in Fig. 3, where we show accretion rate versus black hole mass with the parameters Kerr parameter and inclination angle. We obtained this grid by applying the scaling laws $M \propto \dot{L}/L \cdot M_0$ and $M = (\dot{T}/T_{\text{eff}})^2 \cdot \sqrt{L/L} \cdot M_0$ where $\dot{L} = \dot{L}(a,i)$ and $\dot{T} = \dot{T}(a,i)$ are the calculated functions for luminosity and effective temperature of the disk at arbitrary but fixed values of $M = M_0$ and $\dot{M} = \dot{M}_0$. $T_{\text{eff}}$ and $L$ are the observed values of the radiation field for which we took $T_{\text{eff}} = 4 \cdot 10^4K$ and $L = 3 \cdot 10^5L_\odot$ as our reference frame for the Galactic Center. Again, with better observational data at hand, one can easily adapt this grid by simple interpolation to test the black hole scenario for Sgr A*.

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References

(in alphabetical order)
Figure 3: The shaded area limits the possible parameters $M$ and $\dot{M}$ for a black hole that matches a luminosity of $L = 3 \cdot 10^5 L_\odot$ and an effective temperature $T_{\text{eff}} = 4 \cdot 10^4 K$ for a grid of angular momenta $a$ and inclination angles $i$. The thick arrows indicate how the whole grid shifts if one increases the luminosity by a factor 2 or reduces the effective temperature by one tenth respectively.

References:

Bardeen, J.M., 1970, Nat 226, 64
Clarke C.J., Lin D.N.C., Pringle J.E., 1990, MNRAS 242, 439
Cox P., Laureijs R., 1989, In: Morris M. (ed.), The Galactic Center. Proc. IAU Symp. 136, p. 121
Cox P., Mezger P.G., 1989, A&AR 1, 49
Cunningham C., 1975, ApJ 202, 788
Duschl W.J., Tscharnuter W.M., 1991, A&A 241, 153
Eckart A., Genzel R., Krabbe A., Hofmann R., van der Werf P.P., Drapatz S., 1992, Nat 355, 526
Falcke H., Mannheim K., Biermann P.L., 1992, to be submitted
Falcke H., Scherer H., Schmutzler T., Biermann P.L., 1992, in preparation
Genzel R., Townes C.H., 1987, ARA&A 25, 377
Hessman F.V., 1991, A&A 246, 137
Kato S., Fukue J., Inagaki S., Okazaki A.T., 1982, PASJ 34, 51
Kerr R., 1963, Phys.Rev.Lett. 11, 237
Krabbe A., Genzel R., Drapatz S., Rotaciuc V., 1991, ApJ 382, L19-L22
Krichbaum T.P., Zensus J.A., Witzel A., Mezger P.G., Standke K. et al., 1992, in preparation
Novikov I.D., Thorne K.S., 1973, Black Hole Astrophysics. In: DeWitt C., DeWitt B. (eds.), Les astres oculus, Gordon & Breach, New York, p.343-450
Page D.N., Thorne K.S., 1974, ApJ 191, 499
Roberts D.A., Goss W.M., van Gorkom J.H., Leahy J.P., 1991, ApJ 366, L15
Rosa M.R., Zinnecker H., Moneti A., Melnick J., 1992, A&A 257,515
Sanders R.H., 1992, Nat 359,131
Sanders R.H., Lowinger Th., 1972, AJ 77, 292
Sellgren K., 1988, in: Morris, M. (ed.), The Galactic Center. Proc. IAU Symp. 136, p. 477
Shakura N.I., Sunyaev R.A., 1973, A&A 24, 337
Thorne K.S., 1974, ApJ 191, 507
von Weizsäcker C.F., 1948, Zeitschrift f. Naturf. 3 a, 524
Zylka R., Mezger P.G., Lesch H., 1992, A&A 261, 119 (ZML92)
Zylka R., Mezger P.G., Wink J.E., 1990, A&A 234, 133