Heavy neutrino ball as a possible solution to the “blackness problem” of the Galactic center

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Abstract

It has been recently shown (Tsiklauri and Viollier, 1998, ApJ 500, 591) that the matter concentration inferred from observed stellar motion at the galactic center (Eckart and Genzel 1997, MNRAS 284, 576 and Genzel et al. 1996, ApJ 472, 153) is consistent with a supermassive object of $2.5 \times 10^6$ solar masses, composed of self-gravitating, degenerate heavy neutrinos. It has been furthermore suggested (Tsiklauri and Viollier, 1998, ApJ 500, 591) that the neutrino ball scenario may have an advantage that it could possibly explain the so-called “blackness problem” of the galactic center. Here, we present a quantitative investigation of this statement, by calculating the emitted spectrum of Sgr A* in the framework of standard accretion disk theory.

Keywords: Accretion, accretion disks; Dark matter; Galaxy: center; Radiation mechanisms: thermal

1. Introduction

Identification of the nature of the enigmatic radio source Sgr A* at the galactic center has been a long-standing puzzle. Observations of stellar motions at the galactic center (Eckart and Genzel 1997, Genzel et al. 1996) and low proper motion (≤ 20 km s$^{-1}$; Backer 1996) of Sgr A* indicate that, on the one hand, it is a massive $(2.5 \pm 0.4) \times 10^6 M_\odot$ object dominating the gravitational potential in the inner ≤ 0.5 pc region of the galaxy. On the other hand, observations of stellar winds and other gas flows in the vicinity of Sgr A* indicate that the mass accretion rate $\dot{M}$ is about $6 \times 10^{-6} M_\odot$ yr$^{-1}$ (Genzel et al. 1994). This fact implies that the observed luminosity of the central object should be more than $10^{40}$ erg s$^{-1}$, assuming that the radiative efficiency is the customary 10%. However, observations reveal that the bolometric luminosity is actually less than $10^{37}$ erg s$^{-1}$. This discrepancy has been a source of exhaustive debate in the recent past. The broad-band emission spectrum of Sgr A* can be reproduced either in the quasi-spherical accretion model (Melia 1992, 1994) with $\dot{M} \approx 2 \times 10^{-4} M_\odot$ yr$^{-1}$ or by a combination of disk plus radio-jet model (Falcke et al. 1993a, 1993b). As pointed out by Falcke and Melia (1997), quasi-spherical accretion seems unavoidable at large radii, but the low actual luminosity of Sgr A* points toward a much lower accretion rate in a starving disk. Therefore, Sgr A* can be described by a model of a fossil disk fed by quasi-spherical accretion. Another successful model which is consistent with the observed emission spectrum of Sgr A* has been developed by Narayan et al. (1995, 1998), and

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in the framework of the Thomas–Fermi model at finite temperature were taken into account in Bilić and Viollier (1998a). A theorem was proven by Bilić and Viollier (1998b) which in brief states that the extremization of the free energy functional of a system of self-gravitating fermions, described by the general relativistic Thomas–Fermi model, is equivalent to solving Einstein’s field equations.

2. The model

The basic equations which govern the structure of cold neutrino balls have been derived in the series of papers (Viollier 1994, Viollier et al. 1993, Viollier et al. 1992, and Tsiklauri and Viollier 1996); here we adopt the notation of Tsiklauri and Viollier (1996). In this notation the enclosed mass of the neutrinos and antineutrinos within a radius \( r = r_s \xi \) of a neutrino ball is given by

\[
M_c = 8 \pi \rho_c r_s^3 \left( -\xi^2 \frac{d \theta(\xi)}{d \xi} \right) \equiv 8 \pi \rho_c r_s^3 (-\xi^2 \theta') ,
\]

(1)

where \( \theta(\xi) \) is the standard solution of the Lane–Emden equation with polytropic index \( 3/2 \), \( r_s \) is the Lane–Emden unit of length and \( \rho_c \) is the central density of the neutrino ball.

In the standard theory of steady and geometrically thin accretion disks, the power liberated in the disk per unit area is given by (Perry and Williams 1993)

\[
D(r) = -\frac{M \Omega H r}{4 \pi} \left[ 1 - \left( \frac{R_i}{r} \right)^2 \left( \frac{\Omega}{\Omega_i} \right) \right] .
\]

(2)

Here \( \Omega \) is the angular velocity of the accreting matter, \( R_i \) is the inner edge of the disk and \( \Omega_i \) denotes the angular velocity at the radius where its derivative with respect to \( r \) vanishes due to the deviation from the Keplerian law of rotation. Finally, the prime denotes the derivative with respect to \( r \). Since the motion of accreting matter in the bulk of the disk is Keplerian, we assume that the angular velocity is given by

\[
\Omega(r) = \sqrt{GM_c(r)/r^3} .
\]

(3)

In the case of a black hole \( M_c(r) = \text{const.} = M_{bh} \), whereas in our case \( M_c(r) \) is determined by Eq. (1).
Fig. 1. Comparison of theoretical and observed spectra of Sgr A\(^{*}\). The thick solid line corresponds to the case of a neutrino ball of total mass 2.5 \(\times 10^6\) \(M_\odot\), with \(m = 4 \times 10^{-3}\), while the thin solid line represents \(m = 10^{-4}\). The short-dashed line describes the calculation with a 2.5 \(\times 10^6\) \(M_\odot\) black hole, with \(m = 10^{-4}\) and an accretion disk extending from 3 to 10\(^4\) Schwarzschild radii. The long-dashed line corresponds to the case when \(m\) is artificially reduced to 10\(^{-5}\). The data points are taken from Narayan et al. (1998) who compiled all available data in the published sources. Data points in the \(< 40\) GHz region are upper bounds. Note, that the thick solid line fits the most reliable data points with the error bars.

Throughout this paper we take the outer radius of the disk as 10\(^5\) Schwarzschild radii, since this value yields the correct slope of the left wing of the black body spectrum (see further Fig. 1), especially in the part where data are the most reliable, i.e. datapoints with error-bars. The radius of a neutrino ball with a mass 2.5 \(\times 10^6\) \(M_\odot\), composed of neutrinos and antineutrinos with masses \(m_\nu = 1.2\) keV/\(c^2\) for \(g = 2\) or \(m_\nu = 14.3\) keV/\(c^2\) for \(g = 1\), is equal to 1.06 \(\times 10^5\) Schwarzschild radii of a black hole with the same mass, thus the accretion disk is fully immersed in the neutrino ball. Moreover, as in our case there is no last stable orbit, accretion may in principle continue as \(r\) tends to zero, where \(\Omega(r)\) and \(\Omega'(r)\) assume the values

\[
\Omega(0) = \sqrt{\frac{8\pi G\rho_s}{3}}, \quad \Omega'(0) = \frac{1.5\pi G\rho_s}{r_s \Omega(0)}.
\]  

Of course the latter result is of rather academic interest, because in reality the accreting matter will be diverted at the origin in the form of an outflow which will inevitably stream away perpendicular to the disk plane. The excess matter which has spiraled down to the very center will be pushed out of the plane due to the gas pressure of the accreting matter in the disk. It is important to note that this outflow will differ considerably from a jet shooting out of an accretion disk around a black hole. In the latter case, the jets manifest themselves as strong emitters mostly in the radio band due to the synchrotron radiation produced by the electrons moving at highly relativistic velocities, whereas the outflow from the accretion disk immersed in a neutrino ball will be practically unobservable, since the outflowing matter will be cold as it radiated off its energy while spiraling down in the disk (see further Fig. 2). Moreover, the particles will be moving at non-relativistic velocities because of the shallowness of the gravitational potential of the neutrino ball that is much more spatially extended than a black hole. It is worthwhile to note that, even at a constant accretion rate of 6 \(\times 10^{-6}\) \(M_\odot\) yr\(^{-1}\), the baryonic mass acquired by the neutrino ball within the age of the universe of 10 Gyr would be of the order of 6 \(\times 10^4\) \(M_\odot\), which is small compared to the mass of the neutrino.
ball. However, for the other allowed extreme value of the accretion rate, namely $2 \times 10^{-4} M_\odot$, the over the age of the universe accumulated baryonic matter may pose a problem for our model, especially since that the best fit of our model is achieved for this value of $M$. One may suggest that such amount of the baryonic matter will collapse and form a supermassive black hole. In our opinion, this scenario can be bypassed by the following argument. The above mentioned outflow of the excess baryonic matter, after cooling down (which would obviously take place after loss of kinetic energy) could enter star formation phase. It is known that within 0.1 pc there are about $10^4$ stars at the Galactic center which may have formed out of this baryonic outflow. Further, the formed stars could disperse away by two-body swing-by mechanism avoiding the collapse.

Numerical analysis shows that initially, as the matter spirals towards the center, $\Omega'(r)$ is negative. From Eq. (4) we gather that the central value for $\Omega'$ is finite and positive, thus there exists a point at which $\Omega'$ crosses zero. This is precisely the point where the angular velocity attains its maximal value. Numerically, this happens at $\xi_i = R_i/r_n = 8.25 \times 10^{-4}$. Note that this position is quite close to the center of the ball since its radius in dimensionless units is $\xi_1 = 3.65375$ (Cox and Giuli 1968). Such a behavior of $\Omega(r)$ is quite interesting since, in the neutrino ball scenario, there is neither a last stable orbit nor a stiff stellar surface (as in the case of accretion onto a neutron star). Basically, this is a consequence of the nontrivial mass distribution determined by the Lane–Emden equation.

We now assume that the gravitational binding energy released is immediately radiated away locally according to the Stefan–Boltzmann’s law,

$$D(r) = \sigma T(r)^4, \quad (5)$$

with $\sigma$ denoting the Stefan–Boltzmann constant. The effective temperature can be derived using Eqs. (1)–(3) and (5) yielding

$$T_{\text{eff}}(\xi) = \left[ \frac{M \tilde{\Omega} \Omega' r_n}{4 \pi \sigma} \frac{3 \theta'}{\xi} \right]^{1/4} \left[ 1 - \frac{\xi_i}{\xi} \tilde{\Omega}_t \frac{1}{\partial \xi (\xi)} \right]^{1/4}. \quad (6)$$

Here we have introduced the quantities

$$\tilde{\Omega} = \sqrt{\frac{2.5 \times 10^6 M_\odot G}{r_n^3 (\xi^4 \theta')^2}}, \quad \tilde{\Omega}' = \frac{2.5 \times 10^6 M_\odot G}{2 \Omega r_n^3 (\xi^4 \theta')^2}.$$  

$$(\xi^4 \theta')_1 = 2.71406 \text{ (Cox and Giuli 1968)} \quad \text{and} \quad \tilde{\Omega}_t = \frac{\Omega(\xi_1)}{\tilde{\Omega}}.$$  

Once the temperature distribution in the accretion disk is specified, we may calculate its luminosity using

$$L_\nu = \frac{16 \pi^2 h r_n^2 \cos{\iota} \nu^3}{c^2} \int \frac{\xi \ d\xi}{\exp{[h/\nu]} - 1}. \quad (7)$$

where $h$ is Planck’s constant, $k_b$ denotes Boltzmann’s constant and $\iota$ is the disk inclination angle which we assume to be 60° as it is a mid-value of the allowed range (0 to 1). Following Narayan et al. (1998), we parameterize the accretion rate in terms of the Eddington limit accretion rate, i.e. $\dot{M} = m M_{\text{Edd}} M_\odot \text{ yr}^{-1}$, where $M_{\text{Edd}} = 10L_{\text{Edd}}/c^2 = 1.39 \times 10^{18} (M/M_\odot) \text{ g s}^{-1} = 2.21 \times 10^{-8} (M/M_\odot) M_\odot \text{ yr}^{-1}$. Melia (1992) has estimated $M$ as $\approx 2 \times 10^{-4} M_\odot$ yr$^{-1}$ using 600 km s$^{-1}$ for the wind velocity, whereas Genzel et al. (1994) obtained $M \approx 6 \times 10^{-6} M_\odot$ yr$^{-1}$ using 1000 km s$^{-1}$ for the wind velocity. These values translate into $10^{-4} < m < 4 \times 10^{-3}$ in terms of the Eddington units. Following again Narayan et al. (1998), we use these two values as the lower and upper limits for this quantity.

3. Discussion

Results of our numerical calculations are presented in Fig. 1, where we plot the quantity $v_{\text{L,}}$, calculated using Eq. (7). Data points are taken from Table 1 in Narayan et al. (1998). The thick solid line corresponds to the case of a neutrino ball with $m = 4 \times 10^{-3}$, whereas the thin solid line corresponds to $m = 10^{-4}$. The short-dashed line represents the calculation with a $2.5 \times 10^6 M_\odot$ black hole with $m = 10^{-4}$ and an accretion disk extending from 3 to $10^5$ Schwarzschild radii. The long-dashed line corresponds to the case when $m$ is artificially brought down to $10^{-9}$. As we see from Fig. 1, and as also was pointed out by Narayan et al. (1998), the latter two curves provide a poor fit to the observational data. Actually, this is the major rea-
son why the standard accretion disk theory was abandoned as a possible candidate for the description of the emitted spectrum from Sgr A*. However, as originally was pointed out in Tsiklauri and Viollier (1998a) in the neutrino ball scenario, the accreting matter experiences a much shallower gravitational potential than in the case of the black hole with the same mass, and therefore less viscous torque will be exerted. The radius of a neutrino ball of total mass \(2.5 \times 10^6 M_\odot\), which is composed of self-gravitating, degenerate neutrinos and antineutrinos of mass \(m_\nu = 12.0 \text{ keV}/c^2\) for \(g = 2\) or \(m_\nu = 14.3 \text{ keV}/c^2\) for \(g = 1\), is \(1.06 \times 10^5\) larger than the Schwarzschild radius of a black hole of the same mass. In this context it is important to note that the accretion radius \(R_\Lambda = 2GM/v_w^2\) for the neutrino ball, where \(v_w \approx 700 \text{ km/s}\) is the velocity of the wind from the IRS 16 stars, is approximately 0.02 pc (Coker and Melia 1997), which is slightly less than the radius of the neutrino ball, i.e. \(0.02545 \text{ pc}\) (for \(m_\nu = 12.0 \text{ keV}/c^2\) for \(g = 2\) or \(m_\nu = 14.3 \text{ keV}/c^2\) for \(g = 1\)). Therefore, in the neutrino ball scenario, the captured accreting matter will always experience a gravitational pull from a mass less than the total mass of the ball. One can see from Fig. 1, that for this very reason the theoretical spectrum in the case of the neutrino ball with \(m = 4 \times 10^{-3}\) gives a much better fit than in the case of a black hole for any (even unrealistically lowered) values of \(m\). Discrepancies between the theoretical and observed spectra appear in the case of the neutrino ball for frequencies < 40 GHz and \(\geq 10^{14}\) Hz.

At the higher end (\(\geq 10^{14}\) Hz) of the spectrum, the discrepancy is due to the fact that our model does not incorporate effects of Compton-scattered synchrotron radiation (which causes the second peak on the left in Fig. 1 of Narayan et al. (1998)). Our model is based on the simple-minded assumption of a steady, geometrically thin accretion disk which radiates off the gravitational binding energy locally, according to the black-body radiation law. However, even in this simplified framework, our model gives a reasonable fit in the radio to near infrared part of the spectrum. Besides, it is important to note that, as it has been shown by Falcke and Melia (1997), the evolution of an accretion disk can be considerably influenced by the deposition of mass and angular momentum by an infalling Bondi–Hoyle wind. The major result of their paper is that the modification of the standard accretion disk model, by taking into account the contribution from the Bondi–Hoyle wind and considering the physical picture of accretion process in dynamics, yields significant changes in the emitted spectrum. In fact, it produces an infrared bump, in addition to the Big Blue Bump, due to the deposition of energy in the outer part of the fossil accretion disk. Our paper is based on the standard accretion disk model, i.e. without modifications arising from taking into account effects from the wind. In our case the gravitational potential is shallower than in the case of a supermassive black hole with the same mass. Therefore, taking into account effects from the Bondi–Hoyle wind and considering the non-steady problem (as in the case of Falcke and Melia’s paper), both bumps will be shifted into the lower frequency domain. Thus the incorporation of Falcke and Melia’s model of the accreting flow into our scenario of the dark matter distribution at the galactic center would presumably produce a better fit in the \(\leq 40\) GHz part of the spectrum.

It is important to address the issue of consistency of our model with intrinsic source size versus frequency data. For the test we take the data of emission wavelength \(\lambda = 7 \text{ mm}\) (Bower and Backer 1998) and 3.5 mm (Rogers et al. 1994, Krichbaum et al. 1994). The upper limits on the intrinsic source size are \(< 4.1\) AU (Bower and Backer 1998) for 7 mm and \(< 1.1\) AU (Rogers et al. 1994) and \(2.8 \pm 1.2\) AU (Krichbaum et al. 1994) for 3.5 mm assuming a distance to the galactic center of 8.5 kpc. Now, we have to estimate the radial location of the circles of the accretion disk in our model, emitting at these two wavelengths. For this purpose we assume that the corresponding temperature of a circle can be determined by the Wien displacement law \(\nu_m \approx 3k_bT/h \approx 6 \times 10^{10}T\) Hz (Lang 1974), i.e. we assume that the maximal frequency (wavelength) in the brightness distribution given the black body law determines the temperature of the emitting region. This assumption seems reasonable recalling the sharpness of the maxima in the brightness distribution (see Fig. 1 in Lang (1974)). Therefore, we obtain \(T_{7\text{mm}} = 0.71K\) and \(T_{3.5\text{mm}} = 1.43K\). To find out to which values of the radial distance in the accretion disk these two values correspond, we have to use Eq. (6), graphically depicted in the Fig. 2. The values are \(\xi_{7\text{mm}} = 8.71 \times 10^{-2}\) and \(\xi_{3.5\text{mm}} = 1.145 \times 10^{-3}\). The final predictions of our model would be twice these values (diameter of the emitting circle) which in di-
mensional units are 2.50 AU and 3.29 AU for 7 mm and 3.5 mm, respectively. Thus we conclude that for 7 mm our model is consistent with the observations by Bower and Backer (1998); the same applies to the data by Krichbaum et al. (1994) for 3.5 mm. However, currently some of the VLBI observations at millimeter wavelength stand in conflict with each other (Bower and Backer 1998). Therefore, the discrepancy of our estimates with the Rogers et al. (1994) data is a matter of debate. Another important requirement which our model does satisfy is the lower limit on the size derived from the scintillation experiments (Gwinn et al. 1991). These experiments imply that the source diameter should be > 0.1 AU for 0.8 mm wavelength. Our estimates show that at this wavelength the source diameter is 34.11 AU which corroborates the validity of our model.

As we can conclude from the latter paragraph, our model satisfies the source versus frequency constraints. However, it seems unlikely that such low temperatures as required by our model, especially close to the center of the neutrino ball, are actually realized, as the Galactic center is immersed in a hot radiation field. So far, the lowest temperature of one of the (black body radiation) emitting components introduced by Zylka, Mezger and Lesh (1992), was estimated to be 30 K, as a possible alternative to the self-absorbed synchrotron emission. Thus, we do not claim that in the mm wave-length band (which corresponds to disk temperatures of order few Kelvin) our model is capable of explaining the emitted spectrum reliably. The fit of the spectrum at these frequencies (< 40 GHz), based on standard accretion disk theory for a disk immersed in the field of the neutrino ball, is anyway not good, and it seems that some other, presumably non-thermal mechanism is responsible for the radio emission of Sgr A*. Moreover, as has been shown by Reynolds and McKee (1980), the compact radio source at the Galactic center could be a pulsar, with total emitting power comparable to that of the Crab pulsar. These authors showed that Sgr A* can be understood in the framework of a number of dynamically self-consistent models of incoherent synchrotron sources which are energetically comparable with to the energy output of a few $10^{38}$ erg s$^{-1}$ like the Crab pulsar. The radio pulsar, together with a Shakura–Sunyaev disk embedded in the shallow gravitational potential of the neutrino ball, may be the key to the understanding of the emission spectrum of Sgr A*. In this context, it is perhaps important to point out that the low proper motion of the central radio source ($\leq 20$ km s$^{-1}$; Backer 1996) could be explained by a slowly moving pulsar near the minimum of the gravitational potential of the neutrino ball, a possibility which of course would be excluded in a supermassive black hole scenario.

Apart from emission of high-energy radiation by the pulsar, and X-ray emission of the neutrino ball through radiative decay of the constituent neutrinos into light neutrinos, our model would be incapable of describing of X-rays and gamma-rays. First, even standard accretion disk theory around a central black hole cannot account for the emission of radiation above ultra-violet.

The simplest model which might produce X-rays is the two-component plasma model by Shapiro, Lightman and Eardley (1976). However, in the case of a neutrino ball with the physical parameters mentioned above, it is impossible to get X-rays and gamma-rays from the accretion disk by definition. In order to get an appreciable fraction of the rest mass of the electron converted into X-rays, the particles need to reach a sizable fraction of the velocity of light, which would be impossible in our scenario as the escape velocity from the center of the neutrino ball is about 1400 km s$^{-1}$. This is, in fact, the reason why our model can explain the blackness problem of the Galactic center.

Let us now take an unprejudiced view on the high-energy data: In the 0.8-2.5 keV band the data available from ROSAT (Predehl and Trümper 1994) have a resolution of $\sim 20''$; in the 2-10 keV band data available from ASCA (Koyama et al. 1996) the resolution is $\sim 1''$. The 35–150 keV data from SIGMA (Goldwurm et al. 1994) have a resolution of $\sim 15''$, while the EGRET data (Merck et al. 1996) from 30 MeV to 10 GeV have a resolution of $\sim 1''$. The intrinsic size of the accretion disk (which is about the size of the neutrino ball) is about 0.65 pc which is much smaller than the resolution of current X-ray or gamma-ray detectors. Even the measurement by Predehl and Trümper (1994), who established that the X-ray source is within a 10$''$ (0.5 pc) distance from the Sgr A*, is not conclusive. As discussed in detail in Tsiklauri and Viollier (1998a), a neutrino ball would also produce X-rays via the radiative decay of the heavy into light neutrinos. Tsiklauri and Viollier (1998a) have estimated that the luminosity of this emission line at energy $\sim m_e c^2/2$
(which would not be a sharp line due to scattering by the existing matter at the Galactic center) should be $L_{\nu} \leq 1.45 \times 10^{34} \text{erg/s}$. In fact, this luminosity is consistent with the observations by Predehl and Trümper (1994).

Finally, we would like to emphasize that the idea that Sgr A$^*$ may be an extended object rather than a supermassive black hole is not new (see e.g. Haller et al. 1996, Sanders 1992). To our knowledge all previous such models assume that the extended object is of a baryonic nature, e.g. a very compact stellar cluster. However, it is commonly accepted that these models face problems with stability, and it has been questioned whether such clusters are long-lived enough, based on evaporation and collision time-scales stability criteria (for a different point of view, see Moffat 1997). In fact, since our model involves the accretion of a significant baryon mass over the lifetime of the Galaxy, its success requires that this baryonic mass undergoes star formation, followed by evaporation of the resulting stellar cluster. Our model of Sgr A$^*$ is surprisingly simple while it satisfies all current observational constraints: First, a neutrino ball is a stable object quite alike an ordinary baryonic star, though much more massive, with the difference that its self-gravity is compensated by the degeneracy pressure of the neutrinos rather than thermal pressure as in the case of a black hole with current observational resolution ($\approx 10^5$ Schwarzschild radii) of the observations of proper stellar motions (Eckart and Genzel 1997, Genzel et al. 1996). Third, a neutrino ball of this mass can explain its low proper motion ($\leq 20 \text{ km s}^{-1}$; Backer 1996). Fourth, as a bonus of our model, the neutrino ball is extended enough to provide a much shallower gravitational potential than a $2.5 \times 10^6 M_{\odot}$ black hole for the accreting matter, thus producing a reasonable emission flux.

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References


