Sgr A*: A supermassive black hole or a spatially extended object?

F. Munyaneza, D. Tsiklauri and R.D. Viollier

Physics Department, University of Cape Town, Rondebosch 7701, South Africa

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1email: tsiklauri@physci.uct.ac.za, http://pc021.phy.uct.ac.za/tsiklauri/

2email: viollier@physci.uct.ac.za
ABSTRACT

We report here on a calculation of possible orbits of the fast moving infrared source S1 which has been recently observed by Eckart & Genzel (1997) near the Galactic center. It is shown that tracking of the orbit of S1 or any other fast moving star near Sgr A* offers a possibility of distinguishing between the supermassive black hole and extended object scenarios of Sgr A*. In our calculations we assumed that the extended object at the Galactic center is a non-baryonic ball made of degenerate, self-gravitating heavy neutrino matter, as it has been recently proposed by Tsiklauri & Viollier (1998a,b).

Subject headings: black hole physics — celestial mechanics, stellar dynamics — dark matter — elementary particles — Galaxy: center

In spite of the vast and tantalizing work undertaken to resolve the issue of the existence of supermassive black holes (BH) at the centers of galaxies, it seems fair to say that, in this case, the jury is still out (for a current status see e.g. a review paper by Ho 1998). The discovery of quasars in the early 1960’s provoked the idea that these extremely powerful emission sources draw their energy from accretion of matter onto compact, supermassive objects of $10^6$ to $10^9$ solar masses. This has led many to believe that these objects are supermassive black holes (Zeldovich & Novikov 1964; Salpeter 1964; Lynden-Bell 1969). However, as it has also often been pointed out (e.g. Kormendy & Richstone 1995, Maoz 1998), the current belief of the scientific community that the driving engines of AGNs are actually supermassive black holes largely rests on the implausibility of alternative explanations, in particular, explanations which are based on some form of clustered baryonic matter. In this context, it is worthwhile to recall so-called “totalitarian principle of physics” (Ostriker, 1971). This principle, which was originally formulated by the late British novelist T.H. White as the governing principle for a colony of ants, states that “anything not forbidden is compulsory.” It has been used to advocate many speculative (at those days) ideas both in particle physics and in astrophysics. For example, the possible existence of neutron stars had been predicted in the early 1930’s, however until they were actually detected in the late 1960’s, they seemed to be too exotic to be credible for the scientific community at large. Thus, in order to test the supermassive BH paradigm, acceptable alternative models for objects such as Sgr A* ought to be developed. In fact, we have shown (Tsiklauri & Viollier 1998a) that the matter concentration observed through stellar motion at the Galactic center (Eckart & Genzel 1997 and Genzel et al. 1996) is consistent with a supermassive object of $2.5 \times 10^6$ solar masses.
consisting of self-gravitating, degenerate heavy neutrino matter. While in the limit of neutrino masses of a few hundreds of keV/c², which corresponds to the Oppenheimer-Volkoff limit (Bilić et al. 1998), the BH and neutrino ball scenarios are virtually indistinguishable, they differ substantially for neutrino masses between 10 to 20 keV/c². In fact, the observational data (Eckart & Genzel 1997 and Genzel et al. 1996) on the compact dark object at the Galactic center restrict the neutrino mass to \( m_\nu \geq 12.0 \text{ keV/c}^2 \) for \( g = 2 \) or \( m_\nu \geq 14.3 \text{ keV/c}^2 \) for \( g = 1 \), where \( g \) is the spin degeneracy factor of the neutrino. Using these lower bounds, an acceptable fit to the infrared and part of the radio spectrum emitted by Sgr A* was obtained in the framework of the standard accretion disk theory (Tsiklauri & Viollier 1998b).

The most reliable techniques of deducing the masses of central objects in galaxies are based on stellar proper motions, since stars are direct tracers of the gravitational potential and are not affected by non-gravitational forces, in contrast to gas clouds, for example, which may be vastly affected by existing magnetic fields. Even the most sophisticated techniques developed so far, where the mass of central objects is determined using the first moment of the collisionless Boltzmann equation (also referred to as Jeans equation, Binney & Tremaine 1987; Tsiklauri & Viollier 1998a), are model dependent. Moreover, as was pointed out by Kormendy & Richstone 1995, the results obtained in this approach are quite sensitive to the effects of velocity anisotropy. In fact, an increase of the velocity dispersion towards the center as \( \propto r^{-1/2} \), which, assuming an isotropic velocity distribution could serve as proof of the point-likeness of the central object, can effectively be mimicked by an anisotropic velocity distribution. Although, some progress has been made in removing this degeneracy (see Ho, 1998 for details), there is still ample room for speculations, which models like our own (Tsiklauri & Viollier 1998a,b) try to exploit. While at projected distances from Sgr A* larger than 0.1 pc the number of stars observed within a shell of a given projected thickness is large enough to make the calculation of the velocity dispersion statistically sound, this number drops to only 11 stars (S1-S11) within 0.03 pc, rendering a statistical treatment of the innermost stars around Sgr A* somewhat meaningless. Thus, in this letter we would like to explore the gravitational potential of Sgr A* without using statistics, i.e. studying the motion of individual stars in the vicinity of Sgr A*. Such an analysis has the advantage of being model independent, as our arguments will be solely based on Newtonian dynamics. The idea of tracking individual stars on an appreciable fraction of the orbiting period, in order to distinguish between the supermassive black hole and extended object or neutrino ball scenarios of Sgr A*, was proposed in Tsiklauri & Viollier 1998a.

As an example we investigate here the motion of the fastest (S1) of the eleven stars in the central cluster around Sgr A*. We study the dynamics of the star S1 for two distinct cases: first, assuming that Sgr A* is
a black hole of the mass \(2.61 \times 10^6 M_\odot\) and second, replacing the supermassive black hole by an extended object, i.e., a ball of the same mass, consisting of degenerate, self-gravitating neutrino (and antineutrino) matter. In a previous paper, Tsiklauri & Viollier 1998a have set bounds on the mass of the neutrino, based on the observational data taken form Genzel et al. 1996. Since then, the data points describing the mass enclosed within a given radius have moved inwards, thus putting new constraints on the possible size of the central object. It is therefore worthwhile to reconcile our model with the most recent published data by Genzel et al. 1997, who established that the enclosed mass at the Galactic center within 0.016 pc (the innermost data point) is \((2.65 \pm 0.76) \times 10^6 M_\odot\). Repeating the analysis of Tsiklauri & Viollier 1998a, using these new data, we find that the new bounds on the mass of the neutrino are \(m_\nu \geq 12.07 \text{ keV}/c^2\) for \(g = 2\) or \(m_\nu \geq 14.35 \text{ keV}/c^2\) for \(g = 1\), which slightly reduce the maximal radius of the neutrino ball. Thus, using the value of \(2.61 \times 10^6 M_\odot\) (Genzel et al. 1997) for the mass of the neutrino ball, the radius turns out to be \(2.477 \times 10^{-2}\) pc (we assume that the distance to Sgr A* is 8.0 kpc throughout this letter).

Eckart & Genzel 1997 have presented proper motion data for S1, as well as other stars in the central cluster around Sgr A*. In 1994 the coordinates of S1 were RA=−0.19″ and DEC=−0.04″, with Sgr A* being the origin of the coordinate system, and the x- and y-components of the projected velocity, \(v_x = 650 \pm 400\) km/sec and \(v_y = -1530 \pm 400\) km/sec, respectively, deduced from the 1994 and 1996 data. Here \(x\) is opposite to the RA direction and \(y\) is in DEC direction. We then solve Newton’s equations for two cases (i) a black hole with a mass \(2.61 \times 10^6 M_\odot\) and (ii) a neutrino ball of the same mass, with the neutrino mass fixed at the lower limit allowed by the stellar proper motion data (Genzel et al. 1997). Note, that increasing of the neutrino mass will smoothly interpolate between the scenarios (ii) and (i). A typical result of such calculation is shown in Fig. 1 where we plot the two orbits of S1 corresponding to the BH and neutrino ball scenarios. The neutrino ball is represented by the dotted circle with its center (star) at the position of Sgr A*. The values for \(v_x\) and \(v_y\) are taken as 650 and −1530 km/sec, respectively. Sgr A* and S1 are assumed to be at the same distance from the observer, i.e. the \(z\) coordinate of the star S1, as measured in the line-of-sight from Sgr A*, is zero. Moreover, the velocity component in the line-of-sight of the star S1, \(v_z\), has also been set to zero in this figure. The unknown quantities, \(z\) and \(v_z\), are the major source of uncertainty in determining the intrinsic orbit of the star S1. However, as we will see below, this shortcoming will not substantially affect the predictive power of our model if appropriately dealt with. Finally, the full square labels on the orbits denote time in years. Due to the fact that the gravitational force at a given distance from Sgr A* is determined by the mass enclosed within this distance, the star S1 will be deflected much less in the neutrino ball scenario than in the BH scenario of Sgr A*, as can be seen from Fig. 1.
It is worthwhile to note at this stage that the observational test which we propose is somewhat reminiscent of Rutherford’s experiments at the beginning of this century. These experiments led to abandoning of Thomson’s "pudding" model of the atom (which described atom as an extended positively charged spherical cloud, with electrons like raisins in a pudding whose oscillation around the equilibrium point was providing electromagnetic radiation) and established the current views of the atomic structure of matter and the "compactness" of the nucleus.

Returning back to Fig. 1, it seems that, since the positions of the stars S1-S11 are known to 30 mas accuracy, distinguishing the BH from the neutrino ball scenario for Sgr A* might be possible in a few years time. However, as we will discuss below, this estimate is perhaps too optimistic, since it does not take into account the uncertainties due to the complete lack of information on $z$ and $v_z$. Moreover, as we know, there are also large uncertainties in the determination of $v_x$ and $v_y$. Of course, all these uncertainties will eventually decrease, as more data will become available, since the projected orbit, inclusive $v_z$ and $z$, will be completely determined by the accurate measurement of the position of S1 as a function of time. Thus, as our next step, we will investigate the errors in the velocity components in more detail. To this end, we have performed calculations of the orbit of the star S1 in both BH and neutrino ball scenarios, taking into account the error bars of $v_x$ and $v_y$. The results of this calculation are presented in the Fig. 2. The top panel represents the orbits in the case of a BH, whereas, the lower panel describes the neutrino ball scenario. The spread of the orbits induced by the uncertainties in $v_x$ and $v_y$ is quite large. In the BH scenario, the curves 1, 2 and 4 are bound orbits (ellipses with the BH in one focus), whereas in the neutrino ball scenario only one orbit is bound (curve 2, which is actually a rosette-type orbit). In both cases we assume $z = v_z = 0$. At first sight, it may seem that the results of this calculation are inconclusive, especially in view of the current complete uncertainty in $z$ and $v_z$. However, let us investigate in some more detail the dependence of the orbits presented in the Fig. 2 on these two parameters. In Fig. 3 where we plot the orbits of the star S1 for $v_z = 0$, $v_x$ and $v_y$ being fixed at 650 and $-1530$ km/sec, respectively, and varying $z$. The top panel corresponds to the BH scenario, whereas lower one is for the neutrino ball case. The largest value of $z$ taken in this plot corresponds to the radius of the neutrino ball, i.e. the distance from Sgr A* beyond which there is, obviously, no difference between the BH and neutrino ball scenarios. It is worthwhile to note that in the neutrino ball scenario the dependence on $z$ is relatively small as soon as $z$ is smaller than its radius. This is can be understood by the fact that the potential inside the neutrino ball is approximately of harmonic oscillator-type, where Newton’s equations decouple in Cartesian coordinates. We also conclude from the plot that, by increasing $z$, the orbits become more like straight lines, i.e. they are shifting towards
the lower right corner of the graph. This is in accordance to one’s expectations, since increasing of the \( z \) coordinate means moving away from the scattering center, with less interaction and deflection.

The dependence of the orbits on \( v_z \) is summarized in Fig. 4 which is similar to Fig. 3, but in this case we fix \( z \) to zero, varying \( v_z \) instead. Again, increasing \( v_z \) produces a similar effect as in the case of increasing \( z \) in the previous figure, i.e. larger \( z \)-components of the velocity lead to straightening of the orbit. As increasing \( v_z \) yields a larger velocity for the star, it is clear that faster moving stars will be deflected less than the slower ones. We have thus established that both uncertainty factors, \( z \) and \( v_z \), have similar effects on the orbits. In Fig. 5 two orbits are plotted: the upper-leftmost orbit of S1 corresponding to the neutrino ball scenario (actually, line 4 in the bottom panel of Fig. 2) and the nearest orbit of the same object but for the BH scenario (actually, line 5 in the upper panel of the Fig. 2). From this figure we can conclude that \textit{irrespective} of what the actual values of \( z \) and \( v_z \) are, if the star S1 will eventually be found in the upper-left zone of the graph, then it will clearly rule out the neutrino ball scenario of Sgr A* for the chosen neutrino mass. This graph as well as Fig. 2 is plotted for \( z = v_z = 0 \), and as we have learned from Figs. 3 and 4, any non-zero values of these parameters would just straighten the orbit. Thus, this plot is a good test for the identification of a supermassive black hole, as opposed to an extended object or a neutrino ball at the Galactic center. If the orbit of S1 eventually ends up in the lower right corner, then Sgr A* can be interpreted as either a neutrino ball or a BH with a large \( z \)-parameter. Thus, it seems that as the observations proceed within the next decade, one may tell the difference between the supermassive black hole scenario and neutrino ball model of the Galactic center using this test, since the uncertainties in the projected orbit will decrease in the course of time.

Note: After this work has been completed, we became aware of new results on the central cluster by Ghez et al. 1998. While the details of the plots might change using these new data, the basic results of this letter will be unaffected.
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Fig. 1: Projected orbits of the star S1 in the case of a supermassive BH of a mass $2.61 \times 10^6 M_\odot$ (solid line) and in the case of a neutrino ball (dashed line). The surface of the neutrino ball with the same mass as the BH, and consisting of heavy, degenerate neutrino matter with neutrino masses $m_\nu = 12.07 \text{ keV}/c^2$ for $g = 2$ or $m_\nu = 14.35 \text{ keV}/c^2$ for $g = 1$ is shown by the dotted circle. The neutrino ball has a radius of $9.9182 \times 10^4$ Schwarzschild radii. The star in the upper-right corner denotes Sgr A*. In this plot $v_x = 650$ km/sec, $v_y = -1530$ km/sec and $v_z = z = 0$.

Fig. 2: Projected orbits of the star S1 in the case of a supermassive black hole (top panel) and in the case of a neutrino ball (lower panel) for $v_z = z = 0$. In this graph we explore how the orbits are affected by the uncertainty in $v_x$ and $v_y$. The labels for orbits are: 1: $v_x = 650$ km/sec and $v_y = -1530$ km/sec (median values, orbit is bound in the case of a BH and unbound for the neutrino ball); 2: $v_x = 250$ km/sec and $v_y = -1130$ km/sec (orbits are bound in both cases); 3: $v_x = 250$ km/sec and $v_y = -1930$ km/sec (orbits are unbound in both cases); 4: $v_x = 1050$ km/sec and $v_y = -1130$ km/sec (orbit is bound in the case of a BH and unbound for a neutrino ball); 5: $v_x = 1050$ km/sec and $v_y = -1930$ km/sec (orbits are unbound in both cases). The time labels (filled squares) on the orbits are placed in intervals of 10 years, up to the year 2034.

Fig. 3: Projected orbits of the star S1 in the case of a supermassive BH (top panel) and in the case of a neutrino ball (lower panel). In this graph we explore how the orbits are affected by the uncertainty in the $z$-parameter. The labels for the orbits are given in the graph. Note, that for $z = 0.6388''$, which corresponds to the radius of the neutrino ball for the assumed distance to the Galactic center, the orbits for a BH and neutrino ball are identical, as it should be. In this graph $v_x = 650$ km/sec, $v_y = -1530$ km/sec and $v_z = z = 0$.

Fig. 4: Projected orbits of the star S1 in the case of a supermassive black hole (top panel) and in the case of a neutrino ball (lower panel). In this graph we explore how the orbits are affected by the uncertainty in $v_z$. The labels for the orbits are given in the graph. Here, $v_x = 650$ km/sec, $v_y = -1530$ km/sec and $z = 0$.

Fig. 5: A graph which combines line 4 from the bottom panel of Fig. 2 and line 5 from the upper panel of Fig. 2 for comparison. If the star S1 will eventually be found in the upper-left zone of the graph, i.e. up and left of the overlapping lines (referred to as a black hole zone), this will rule out the neutrino ball interpretation of Sgr A* for the chosen neutrino mass.
Fig. 1

- Black hole
- Neutrino ball
- Neutrino ball surface
Fig. 3

RA (arcsec)

Declination (arcsec)

$v_z = 0, z = 0$
$v_z = 0, z = 0.1''$
$v_z = 0, z = 0.2''$
$v_z = 0, z = 0.6388''$

1994

Declination (arcsec)

RA (arcsec)
**Fig. 5**

- **Declination (arcsec)**
- **RA (arcsec)**

- **black hole zone**
- **black hole or neutrino ball zone**