Comparison of the Black Hole and Fermion Ball Scenarios of the Galactic Center

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Abstract

After a discussion of the properties of degenerate fermion balls, we analyze the orbit of the star S0-1, which has a projected distance of $\sim 5$ light-days to Sgr A*, in the supermassive black hole as well as in the fermion ball scenarios of the Galactic center. It is shown that both scenarios are consistent with the data, as measured during the last 6 years by Genzel and coworkers and by Ghez and coworkers. The free parameters of the projected orbit of a star are the unknown components of its velocity $v_z$ and distance $z$ to Sgr A* in 1995.4, with the $z$-axis being in the line of sight. We show, in the case of S0-1, that the $z - v_z$ phase-space, which fits the data, is much larger for the fermion ball than for the black hole scenario. Future measurements of the positions or radial velocities of S0-1 and S0-2, which could be orbiting within such a fermion ball, may reduce this allowed phase space and eventually rule out one of the currently acceptable scenarios. This could shed some light on the nature of the supermassive compact dark object, or dark matter in general, at the center of our Galaxy.

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1 Introduction

Self-gravitating degenerate neutrino matter has been suggested as a model for quasars, with neutrino masses in the $0.2 \text{ keV} \lesssim m \lesssim 0.5 \text{ MeV}$ range [1] even before the black hole hypothesis of the quasars was conceived [16]. More recently, supermassive compact dark objects consisting of weakly interacting degenerate fermionic matter, with fermion masses in the $10 \lesssim m/\text{keV} \lesssim 20$ range, have been proposed [2, 3, 4, 5, 6] as an alternative to the supermassive black holes that are believed to reside at the centers of many galaxies.

The masses of $\sim 20$ supermassive compact dark objects at the centers of inactive galaxies [7] have been measured so far. The most massive compact dark object ever observed is located at the center of M87 in the Virgo cluster, and it has a mass of $\sim 3 \times 10^9 M_\odot$ [8]. NGC 3115, NGC 4594 and NGC 4374 are galaxies harbouring compact dark objects with the next smaller mass of $\sim 10^9 M_\odot$. If we identify the object of maximal mass with a degenerate fermion ball at the Oppenheimer-Volkoff (OV) limit [9], i.e. $M_{OV} = 0.54 M_{Pl}^3 m^{-2} g^{-1/2} \simeq 3 \times 10^9 M_\odot$, where $M_{Pl} = \sqrt{\hbar c/G}$, this allows us to fix the fermion mass to $\simeq 15 \text{ keV}$ for a spin and particle-antiparticle degeneracy factor of $g = 2$. Such a relativistic object would have a radius of $R_{OV} = 4.45 R_S \simeq 1.5$ light days, where $R_S$ is the Schwarzschild radius of the mass $M_{OV}$. It would thus be virtually indistinguishable from a black hole of the same mass, as the closest stable orbit around a black hole has a radius of $3 R_S$ anyway.

At the lower end of the observed mass range are the compact dark objects located at the center of NGC 4945, M32 and our Galaxy [10] with masses of about 1.3 and 2.6 million solar masses, respectively. Interpreting the Galactic object as a degenerate fermion ball consisting of $m \simeq 15 \text{ keV}$ and $g = 2$ fermions, the radius is $R_c \simeq 21$ light-days $\simeq 7 \times 10^4 R_S$, $R_S$ being the Schwarzschild radius of the mass $M_c = 2.6 \times 10^6 M_\odot$. Such a nonrelativistic object is far from being a black hole. The observed motion of stars within a projected distance of $\sim 5$ to $\sim 50$ light-days from Sgr A* [10], the powerful and enigmatic radio source at the Galactic center, yields, apart from the mass, an upper limit for the radius of the fermion ball $R_c \lesssim 22$ light days. Matter orbiting in an optically thick and geometrically thin accretion disk in or around such a fermion ball will only emit radiation at distances larger than $\sim 10 \text{ mpc}$ from the center, as both the density and the circular frequency become nearly constant near the center of the fermion ball [3]. The spectrum emitted by the disk will thus have a cut-off at frequencies larger than $\sim 10^{13}$
Hz, as is actually observed. Of course, there will be a pile-up and instability of matter within $\sim 10$ mpc, perhaps leading to the formation of stars, as the gravitational tidal forces on nascent stars is much smaller in the fermion ball than in the black hole scenario. These stars may be eventually ejected from the central star cluster by intruder stars in close binary encounters. The formation of such a fermion ball as well as its coexistence at finite temperature with a Galactic halo composed of the same fermions has been discussed by Lindebaum [17] and Bilić [18] respectively, at this conference. The required weakly interacting fermion of $\sim 15$ keV mass cannot be an active neutrino, as it would overclose the Universe by orders of magnitude [11]. However, the $\sim 15$ keV fermion could very well be a sterile neutrino, contributing $\Omega_{d} \simeq 0.3$ to the dark matter fraction of the critical density today. Indeed, as has been shown for an initial lepton asymmetry of $\sim 10^{-3}$, a sterile neutrino of mass $\sim 10$ keV may be resonantly produced in the early Universe with near closure density, i.e. $\Omega_{d} \sim 1$ [12]. As an alternative possibility, the required $\sim 15$ keV fermion could be the axino [13] or the gravitino [14] in soft supersymmetry breaking scenarios.

2 Dynamics of the Stars Near the Galactic Center

We now would like to compare the predictions of the black hole and fermion ball scenarios of the Galactic center, for the stars with the smallest projected distances to Sgr A*, based on the measurements of their positions during the last six years [10]. The projected orbits of three stars, S0-1 (S1), S0-2 (S2) and S0-4 (S8), show deviations from uniform motion on a straight line during the last six years, and they thus may contain nontrivial information about the potential. For our analysis we have selected the star, S0-1, because its projected distance from Sgr A* in 1995.53, 4.4 mpc or 5.3 light-days, makes it most likely that it could be orbiting within a fermion ball of radius $\sim 18$ mpc or $\sim 21$ light-days. We thus may in principle distinguish between the black hole and fermion ball scenarios for this star.

The dynamics of the stars in the gravitational field of the supermassive compact dark object can be studied solving Newton’s equation of motion, taking into account the initial position and velocity vectors at, e.g., $t_{0} = 1995.4$ yr, i.e., $\vec{r}(t_{0}) \equiv (x, y, z)$ and $\dot{\vec{r}}(t_{0}) \equiv (v_{x}, v_{y}, v_{z})$. For the fermion ball
the source of gravitational field is the mass $M(r)$ enclosed within a radius $r$ while for the black hole it is $M_c = M(R_c) = 2.6 \times 10^6 M_\odot$. The $x$-axis is chosen in the direction opposite to the right ascension (RA), the $y$-axis in the direction of the declination, and the $z$-axis points towards the sun. The black hole and the center of the fermion ball are assumed to be at the position of Sgr A* which is also the origin of the coordinate system at an assumed distance of 8 kpc from the sun.

In Figs. 1 and 2 the right ascension (RA) and declination of S0-1 are plotted as a function of time for various unobservable $z$'s and $v_z = 0$ in 1995.4, in the black hole and fermion ball scenarios. The velocity components $v_x = 340$ km s$^{-1}$ and $v_y = -1190$ km s$^{-1}$ in 1995.4 have been fixed from observations. In the case of a black hole, both RA and declination depend strongly on $z$ in 1995.4, while the $z$-dependence of these quantities in the fermion ball scenario is rather weak. We conclude that the RA and declination data of S0-1 are well fitted with $|z| \approx 0.25''$ in the black hole scenario, and with $|z| \lesssim 0.1''$ in the fermion ball case ($1'' = 38.8$ mpc = 46.2 light-days at 8 kpc). Of course, we can also try to fit the data varying both the unknown radial velocity $v_z$ and the unobservable radial distance $z$. The results are summarized in Fig. 3, where the $z-v_z$ phase-space of 1995.4, that fits the data, is shown. The small range of acceptable $|z|$ and $|v_z|$ values in the black hole scenario (solid vertical line) reflects the fact that the orbit of S0-1 depend strongly on $z$. The weak sensitivity of the orbit on $z$ in the fermion ball case is the reason for the much larger $z-v_z$ phase-space fitting the data of S0-1 as shown by the dashed box. The dashed and solid curves describe the just bound orbits in the fermion ball and black hole scenarios, respectively. The star S0-1 is unlikely to be unbound, because in the absence of close encounters with stars of the central cluster, S0-1 would have to fall in with an initial velocity that is inconsistent with the velocity dispersion of the stars at infinity. Fig. 4 shows some typical projected orbits of S0-1 in the black hole and fermion ball scenarios. The data of S0-1 may be fitted in both scenarios with appropriate choices of $v_x, v_y, z$ and $v_z$ in 1995.4. The inclination angles of the orbit’s plane, $\theta = \arccos (L_z/|\vec{L}|)$, with $\vec{L} = m\vec{r} \times \dot{\vec{r}}$, are shown next to the orbits. The minimal inclination angle that describes the data in the black hole case is $\theta = 70^\circ$, while in the fermion ball scenario it is $\theta = 0^\circ$. In the black hole case, the minimal and maximal distances from Sgr A* are $r_{\text{min}} = 0.25''$ and $r_{\text{max}} = 0.77''$, respectively, for the orbit with $z = 0.25''$ and $v_z = 0$ which has a period of $T_0 \approx 161$ yr. The orbits with $z = 0.25''$ and $v_z$
= 400 km s$^{-1}$ or $z = 0.25''$ and $v_z = 700$ km s$^{-1}$ have periods $T_0 \approx 268$ yr or $T_0 \approx 3291$ yr, respectively. In the fermion ball scenario, the open orbit with $z = 0.1''$ and $v_z = 0$ has a “period” of $T_0 \approx 77$ yr with $r_{\text{min}} = 0.13''$ and $r_{\text{max}} = 0.56''$. The open orbits with $z = 0.1''$ and $v_z = 400$ km s$^{-1}$ or $z = 0.1''$ and $v_z = 900$ km s$^{-1}$ have “periods” of $T_0 \approx 100$ yr or $T_0 \approx 1436$ yr, respectively.

3 Implications and Speculations

A fermion ball at the Galactic center could be indirectly observed through the radiative decay of the fermion (assumed here to be a sterile neutrino) into a standard neutrino, i.e. $f \rightarrow \nu \gamma$. If the lifetime for the decay $f \rightarrow \nu \gamma$ is $2.6 \times 10^{19}$ yr, the luminosity of a $M_c = 2.6 \times 10^6 M_\odot$ fermion ball would be $2.8 \times 10^{33}$ erg s$^{-1}$. This is consistent with the upper limit of the X-ray luminosity for the quiescent-state $\sim 2.8 \times 10^{33}$ erg s$^{-1}$ of the source with radius $0.5'' \approx 23$ light-days, whose center nearly coincides with Sgr A*, as seen by the Chandra satellite in the 2 to 7 keV band [15]. The lifetime is proportional to $\sin^2 \theta$, $\theta$ being the unknown mixing angle of the sterile with active neutrinos. With a lifetime of $2.6 \times 10^{19}$ yr we obtain an acceptable value for the mixing angle squared of $\theta^2 = 0.44 \times 10^{-11}$. The X-rays originating from such a radiative decay would contribute at least two orders of magnitude less than the observed diffuse X-ray background luminosity at this wavelength if the sterile neutrino is the dark matter particle of the Universe. The signal observed at the Galactic center would be a sharp X-ray line at $\sim 7.5$ keV for $g = 2$ and $\sim 6.3$ keV for $g = 4$. This line could thus be misinterpreted as the Fe $K_\alpha$ line at 6.67 keV. The X-ray luminosity would be tracing the fermion matter distribution, and it could thus be an important test of the fermion ball scenario. Of course the angular resolution would need to be $\lesssim 0.1''$ and the sensitivity would have to extend beyond 7 keV.

In the fermion ball scenario, the $\sim 10$ ks X-ray burst observed on 26 October 2000 near Sgr A* would have to be explained as a thermonuclear instability or runaway of material accreted or accreting on a neutron star near the center of the fermion ball. With a neutron star accretion rate of $\sim 10^{-9} M_\odot$/yr, this could also account for the strong radio emission of Sgr A* in terms of synchrotron radiation due to $\sim 50$ MeV electrons and positrons, produced in $\pi - \mu$ decays, after inelastic $N + N \rightarrow N + N + \pi$ collisions.
of the infalling $\sim 200$ MeV nucleons hitting the surface of the neutron star. As accreting matter can easily spin up or slow down the rotation of neutron stars, it is perhaps also able to keep the neutron star stationary at the center of the fermion ball for an extended period of time.

In summary, it is important to note that, based on the data of the star S0-1 alone, the fermion ball scenario cannot be ruled out. Similar results are obtained analyzing the S0-2 data. In fact, in view of the $z - v_z$ phase-space, that is much larger in the fermion ball scenario than in the black hole case for both the S0-1 and S0-2 data, there is a reason to treat the fermion ball scenario of the supermassive compact dark object at the center of our Galaxy with the respect it deserves.

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Figure 1: Right ascension of S0-1 versus time for various $|z|$ and $v_x = 340$ km s$^{-1}$, $v_y = -1190$ km s$^{-1}$ and $v_z = 0$ in 1995.4.
Figure 2: Declination of S0-1 versus time for various $|z|$ and $v_x = 340$ km s$^{-1}$, $v_y = -1190$ km s$^{-1}$ and $v_z = 0$ in 1995.4.
Figure 3: The $|z| - v_z$ phase space that fits the S0-1 data.
Figure 4: Examples of typical orbits of S0-1.