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Alternatives to Black Holes: Gravastars and Plugstars

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Abstract

The images collected by the EHT of objects M87* and SgrA* show darkened, but not black areas. So that the immediate identification with supermassive black holes remains questionable. Attention is thus focused on the main alternative candidates: gravastars, which have attracted a great deal of attention for decades. However, none of these models provides any evidence that can successfully confront these observational data. We present an interpretation derived directly from Schwarzschild's inner geometry, in the subcritical case where the intense pressure gradient counterbalances the force of gravity. The object then exhibits a gravitational redshift effect leading to a wavelength ratio of 3, which is remarkably consistent with image analysis. A mechanism is proposed to ensure the self-stability of such objects, which are then referred to as plugstars.

Keywords

Black Hole, Quasar, Janus Cosmological Model

1. Introduction: Alternative to Black Holes

Recent observational data from EHT ref. [1] [2], do not coincide with the expected images of hypermassive black holes. Their central parts, while dark, are not black. Attention was then turned to alternative models, mainly the various models of gravastar, objects hypothesized in a 2001 paper by Pawel O. Mazur and Emil Mottola ref. [3]-[5] as an alternative to the black hole theory. It has the usual black hole metric outside of the horizon, but de Sitter metric inside. On the horizon there is a thin shell of matter. This solution to the Einstein equations is stable and has no singularities. In their original formulation, a gravastar is composed of three regions, differentiated by the relationship between pressure p and energy density ρ. The central region consists of false vacuum or "dark energy", and in this region $p = -\rho$. Surrounding it is a thin shell of perfect fluid f where $p = \rho$. On the exterior is true vacuum, where $p = \rho = 0$. The dark-energy-like behavior of the inner region prevents collapse to a singularity, and the presence of the thin shell prevents the formation of an event horizon, avoiding the infinite blue shift. The inner region has thermodynamically no entropy and may be thought of as a gravitational Bose-Einstein condensate. Severe red-shifting of photons as they climb out of the gravity well would make the fluid shell also seem very cold, almost absolute zero. In addition to the original thin-shell formulation, gravastars with continuous pressure have been proposed. These objects must contain anisotropic stress ref. [6]. Externally, a gravastar appears similar to a black hole: it is visible by the high-energy radiation it emits while consuming matter, and by the Hawking radiation it creates. Astronomers search the sky for X-rays emitted by infalling matter to detect black holes. A gravastar would produce an identical signature. It is also possible, if the thin shell is transparent to radiation, that gravastars may be distinguished from ordinary black holes by different gravitational lensing properties, as null geodesics may pass through ref. [7]. Mazur and Mottola suggest that the violent creation of a gravastar might be an explanation for the origin of our universe and many other universes because all the matter from a collapsing star would implode "through" the central hole and explode into a new dimension and expand forever, which would be consistent with the current theories regarding the Big Bang ref. [8]. This "new dimension" exerts an outward pressure on the Bose-Einstein condensate layer and prevents it from collapsing further. Gravastars also could provide a mechanism for describing how dark energy accelerates the expansion of the universe. One possible hypothesis uses Hawking radiation as a means to exchange energy between the "parent" universe and the "child" universe, and so cause the rate of expansion to accelerate, but this area is under much speculation. Anyway gravastars have been considered as a serious alternative to black holes in the past decades. Stable models of gravastar have been constructed in many of the alternate gravity modelsbesides standard General Relativity. The Randall-Sundrum braneworld model ref. [9] has been apopular alternative to GR, specially in the cosmological and astrophysical context. In ref. [10] gravastar is considered in RS brane gravity. In ref. [11] the model includes the impact of Kuchowicz metric function. In ref. [12] an extension to Gauss-Bonnet gravity. In ref. [13] the collapase of gravastar is driven by a scalar field, taking account of back-reaction effects. In ref. [14] the authors suggest how to detect the gravastar shadow and how one can distinguish from the black hole event horizon while in ref. [15] various electrically charge gravastars configurations are explored. For recent works, see also references [16] [17].

However, to date there has been no successful comparison of data from a gravastar model with the only observational data available for the supermassive objects M87* and SgrA*. In what follows, we present a model, based on Schwazrs-child's inner metric solution, which offers remarkable agreement with these data as they emerge from the current data processing work carried out by the Event Horizon Telescope teams ref. [1] [2].

2. The Schwarzschild model for an Incompressible Fluid Star

In his article from February 1916 ref. [18] Karl Schwarzschild constructed a metric describing the geometry inside a sphere filled with an incompressible fluid. We reproduce this expression exactly as it appears in Equation (35) of the original German edition:

$$\mathrm{d}s^2 = \left(\frac{3\cos\chi_a - \cos\chi}{2}\right)^2 \mathrm{d}t^2 - \frac{3}{\kappa\rho_0}\left(\mathrm{d}\chi^2 + \sin^2\chi\,\mathrm{d}\vartheta^2 + \sin^2\chi\sin^2\vartheta\,\mathrm{d}\phi^2\right) \tag{1}$$

Schwarzschild takes the value c of the speed of light in vacuum to be equal to 1. ρ_0 is the density, which is constant inside the sphere. We have:

$$\kappa = 8\pi G \tag{2}$$

Angles (χ, ϑ, ϕ) are classical spherical coordinates. The characteristic length is given by expression:

$$\hat{R}^2 = \frac{3c^2}{8\pi G\rho_0} \tag{3}$$

We can pass from the angular coordinate to the radial coordinate r, and Euclidean norm of the space vector (x, y, z) as

$$r = \hat{R}\sin\chi \tag{4}$$

The radius of the star is given by:

$$R^* = \hat{R}\sin\chi_a \tag{5}$$

Schwarzschild denotes by f_4 the term g_{tt} of the metric

$$f_4 = \left(\frac{3\cos\chi_a - \cos\chi}{2}\right)^2 \tag{6}$$

The time factor is an expression corresponding to a stationary observer located inside the sphere.

$$f = \frac{3\cos\chi_a - \cos\chi}{2} \tag{7}$$

Then we have

$$\mathrm{d}s = f\mathrm{d}t \tag{8}$$

Schwarzchild then obtained (Equation (10)) as the way in which the pressure inside the sphere varies.

$$(\rho_0 + p)\sqrt{f_4} = konst. = \gamma \tag{9}$$

In this parenthesis, Schwarzchild sums the constant energy density $\rho_0 c^2$ (with $c = 1$) and the pressure. We can consider that the matter at the centre of a star, when the energy density becomes very high, is in the form of radiation, with a radiation pressure:

$$p = \frac{\rho_0 c^2}{3} \tag{10}$$

The modern form of this internal metric ref. [19] is:

$$\mathrm{d}s^2 = \left(\frac{3}{2}\sqrt{1-\frac{R^{*2}}{\hat{R}^2}} - \frac{1}{2}\sqrt{1-\frac{r^2}{\hat{R}^2}}\right)^2 \mathrm{d}t^2 - \left(1-\frac{r^2}{\hat{R}^2}\right)^{-1} \mathrm{d}r^2 - r^2\mathrm{d}\Omega^2 \tag{11}$$

The term $f_4 = g_{tt}$ becomes zero when $\cos\chi_a = 1/3$, *i.e.* when

$$R^* = R_{crit,phys} = \sqrt{\frac{8}{9}}\hat{R} = \frac{c}{3\pi G \rho_0} \tag{12}$$

According to relation (9), as Schwarzschild notes, the pressure at the centre of the star becomes infinite. We are therefore faced with a first physical singularity. As the star's mass increases, at constant density (which could describe a neutron star where the centrifugal force linked to rotation could be neglected), this physical singularity occurs before a geometric singularity. This last occurs when the star's radius identifies with its Schwarzschild radius, *i.e.* when:

$$R^* = R_{crit,geom} = \sqrt{\frac{3c^2}{8\pi G \rho_0}} \tag{13}$$

The two critical radii are linked by the relation:

$$R_{crit,phys} = \sqrt{\frac{8}{9}} R_{crit,geom} \tag{14}$$

We can consider that this situation does not belong to the physical world ref.[20], which amounts to considering that this exact solution to Einstein's equation, independent of time, does not belong to physics, by invoking a "peed of sound"? varying as the square root of the pressure gradient. But if we consider that the medium can be assimilated to radiation, then this speed of propagation becomes that of light. This leads us to consider, as Schwarzschild was the first to do, that the speed of light varies, and can reach an infinite value at the centre of the star. He gives the law of variation of this speed of light in his equation (44):

Die Lichtgeschwindigeit in unserer Kugel

(The speed of light in our sphere)

$$V = \frac{2}{3\cos\chi_a - \cos\chi} \tag{15}$$

This fraction must be multiplied by the value c of the speed of light in a vacuum:

$$V = \frac{2c}{3\cos\chi_a - \cos\chi} \tag{16}$$

This variation in the speed of light when matter reaches conditions of extreme density is considered in ref. [21] [22]. Unlike other attempts at modeling c variable, this model, based on a generalized gauge relation, preserves Lorentz invariance and the fine structure constant. If we assume that the speed of light can take on a value, if not infinite, then at least very high, at the centre of the object, we obtain a situation where the force of pressure balances the force of gravity. All that remains is to examine the stability of such an object.

What happens when it benefits from an influx of matter, which would be the case for a subcritical neutron star receiving matter from a nearby standard star?

If we rely on the mathematical solution, the time factor f then becomes negative, but along a geodesic it is impossible to turn back:

$$\mathrm{d}s > 0 \Rightarrow f\mathrm{d}t > 0 \tag{17}$$

In this central part of the object, the time coordinate t reverses. Following the dynamic group theory of mathematician J.M.Souriau (ref. [23] [24]), this inversion of the time coordinate implies the inversion of energy and mass.

General relativity opposes the presence of negative mass in the universe ref. [25], because of the unmanageable runaway effect. To go a step further, we need to place ourselves in the geometric framework of the Janus model ref. [26].

In this new scheme, masses of opposite signs repel each other. We also conjecture that a gravitational and quantum phenomenon occurs under these conditions of criticality, in which the excess masses are reversed.

The object in criticality, having received mass from the outside, contains an equivalent quantity in a small sphere filled with negative mass and initially centered on the origin.

The presence of negative mass at the star's center only makes a very weak contribution to the gravitational field mainly created by the positive mass. Thus negative mass is expelled from the object and then expelled from the galaxy into the negative-mass environment between galaxies.

We thus obtain a mechanism that guarantees the stability of such subcritical objects, which we propose to call "plugstars"? like an overflow valve that evacuates excess water.

3. Calculation of the Gravitational Redshift

Such objects will exhibit a gravitational redshift effect with respect to a distant observer. This corresponds to:

$$1+z=\frac{\lambda(\text{observer})}{\lambda(\text{emitter})}=\frac{\sqrt{g_{tt}(\text{observer})}}{\sqrt{g_{tt}(R^*)}}=\frac{1}{f(R^*)} \tag{18}$$

In a situation close to criticality:

$$f=\frac{3}{2}\sqrt{1-\frac{8}{9}}-\frac{1}{2}\sqrt{1-\frac{8}{9}}=\frac{1}{3} \tag{19}$$

An observer will therefore see an object whose central part has an attenuated luminosity, such that the ratio of wavelengths resulting from a gravitational redshift effect is

$$\frac{\lambda(\text{observer})}{\lambda(\text{emitter})}=3 \tag{20}$$

4. Observational Data

Let us refer to the images of supermassive objects obtained using the EHT Collaboration (ref. [1] [2]). The chromatic bars provide equivalent temperature values, which are in fact indications of luminosity (Figure 1 and Figure 2). This light, in any case, is emitted by photons of energy $h\nu$. By forming the ratio of maximum and minimum luminosity, we obtain the wavelength ratio.

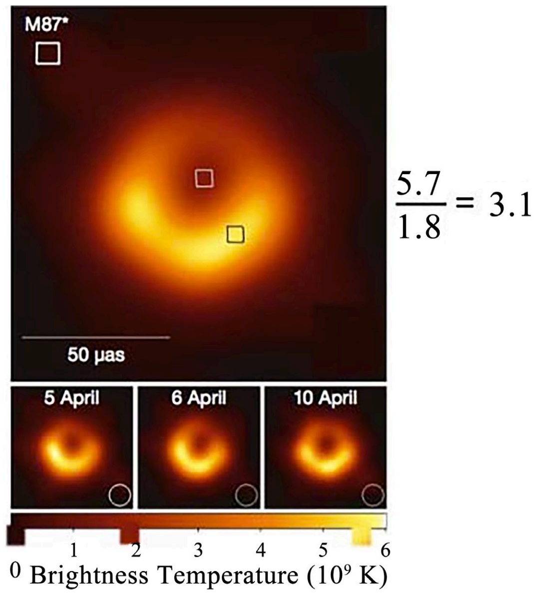

Figure 1. Images of M87*.

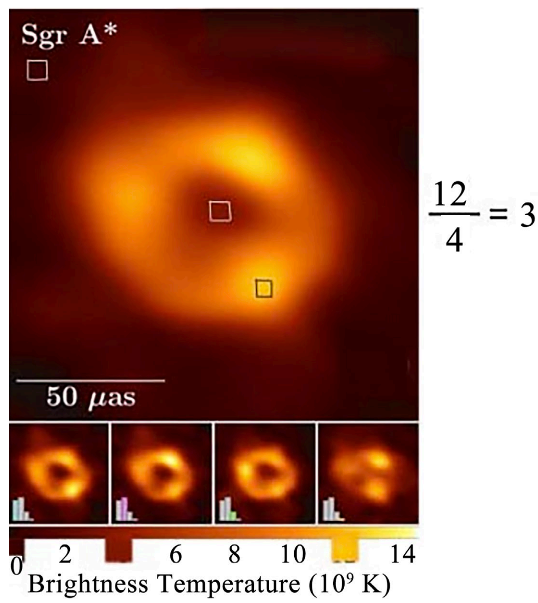

Figure 2. Images of SgrA*.

In the image of the hypermassive object at the centre of M87, the colour bar shows that:

- The maximum equivalent temperature is 5.7×10^9 K.
- The minimum equivalent temperature is 1.8×10^9 K.

The corresponding wavelength ratio is:

$$\frac{\lambda(\text{observer})}{\lambda(\text{emitter})} \approx 3.2 \pm 0.3 \tag{21}$$

On the image of the hypermassive object at the centre of SgrA* the colour bar shows that:

- The maximum equivalent temperature, approximately, is 12×10^9 K.
- The minimum equivalent temperature is 4×10^9 K.

The corresponding wavelength ratio is:

$$\frac{\lambda(\text{observer})}{\lambda(\text{emitter})} \approx 3.0 \pm 0.3 \tag{22}$$

This result is in very agreement with observational data.

Of course, these central objects are not giant neutron stars. But the very high pressure inside them, due to the increase in the speed of light, allows the radiation pressure to counterbalance the force of gravity.

5. Physical Implications of Plugstars

Unlike black holes, these objects:

- have a finite gravitationnal redshift, explaining the darkening of their central part.
- have no horizon or internal singularity.
- are stabilized by the masse inversion processes, in the case of the Janus model, preventing collapse.

When the axes of symmetry of the objects are accessed through the axes of symmetry of the jets, they often correspond to the axes of symmetry of the galaxies ref.[27]. If this phenomenon is general, then these objects would not be formed by mass accretion.

6. An Alternative Interpretation of the Quasar Phenomenon

They could be the result of the convergence of a centripetal density wave, like the one suggested in the Hoag galaxy (**Figure 3**).

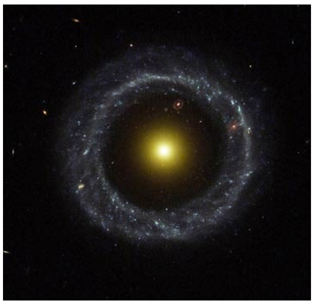

Figure 3. Hoag galaxy.

This galaxy, located in the constellation Serpens Caput, was discovered by Arthur Hoag in 1950. The absence of neighbouring galaxy and debris seems to rule out the possibility that it formed as a result of a collision. Its structure resembles that of a density wave, whose propagation would then be radial.

If a density wave propagates in a galaxy, whether it is a spiral wave or this type of circular, converging wave, its speed of propagation is not that of the matter itself.

This is the classic difference between group velocity and phase velocity. The wave from the Hoag galaxy, if its propagation is centripetal, would then be comparable to a circular tsunami. The rise in density in the wave gives rise to young stars which, emitting in the UV, ionise the medium, making the formation visible, as is the case for spiral waves. In this plasma, if the magnetic Reynolds number is high, this wave will drag along the field lines of the very weak magnetic field (one microgauss) that already exists in the galaxies (see **Figure 4**).

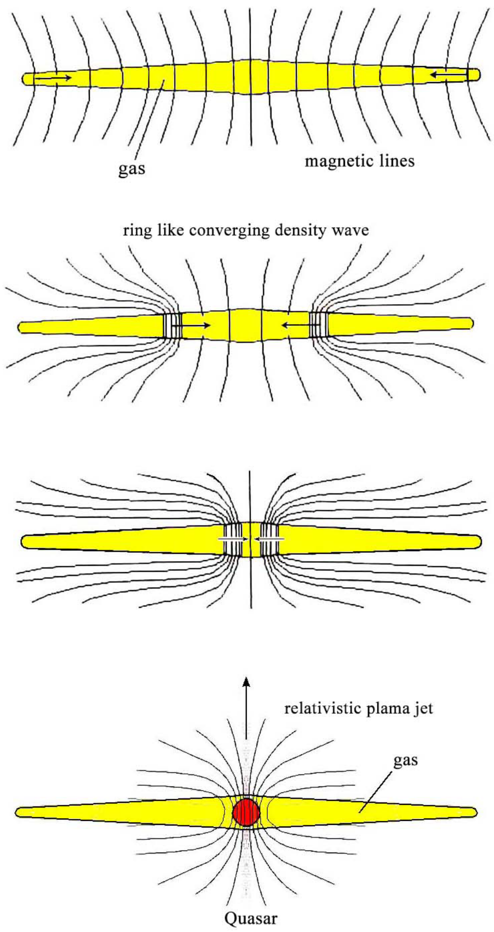

Figure 4. Model for a quasar formation.

Such a rise in the field in the ring could be demonstrated by polarisation measurements.

When the wave would reaches the centre of the galaxy, there would be a sudden rise in density and temperature[1]. Lawson's conditions would be then realised in a considerable mass, triggering a massive production of energy by fusion. Such model would explain the quasar phenomenon.

The convergence of the magnetic field lines would give to the object a very high dipolar magnetic field. The fusion energy would be then focused on the two jets with which M87* is equipped.

This field has a gradient that accelerates charged particles over very large distances, giving them very high energies. This is how cosmic rays would be formed.

The M87* jet is discontinuous, which seems to indicate that the phenomenon is sporadic. The absence of jets for SgrA* would qualify it as an "extinct quasar"? This model is based on the hypothesis of the repetitive birth of spiral density waves.

We still need a theory to explain their appearance. This is what we are currently trying to construct, within the framework of the Janus model, in terms of joint fluctuations in the metrics of positive and negative masses.

We conjecture that future images of hypermassive objects located at the center of galaxies will all present the same wavelength ratio 3.

7. Discussion

To moderate our conclusions, it should be noted that our model is consistent with the images of the objects M87* and SgrA*, which are produced by model-dependent decoding. In any case, it seems difficult to envisage a decoding based on a model in which the central part is completely non-emissive, unless this model is a priori that of a black hole. There will therefore remain a finite gravitational redshift and a maximum/minimum wavelength ratio. The future will tell whether this value close to three can be considered reliable, and above all whether such a ratio will appear in future images of other supermassive objects. It is hoped that images obtained from orbital radio telescopes will provide finer images, which can then be compared with the brightness profiles from the model, which will be produced in a future article. Nevertheless, a few ideas can be outlined. The supermassive objects M87* and Sgr* are obviously not "giant neutron stars". They still need to be modeled. This attempt to describe them as objects with constant density, entirely contained within a sphere, can only be indicative. The fact remains that these objects emit radiation and that a gravitational redshift effect $z = 2$ is present in their central part. Their radius (schematic) is therefore $\sqrt{9/8}R_s = 1.06066R_s$. **Figure 5** shows the schematic evolution of z as a function of distance from the center. If the object is surrounded by a vacuum, the gravitational redshift tends toward zero at infinity.

[1]When the wave causes a rise in density, the angular momentum of the mass concerned is conserved, and the speed of rotation increases. But this phenomenon generates a centrifugal force that cannot be compared with the forces of gravity and pressure. This explains the excellent agreement with the data derived from the Schwarzschild solution.

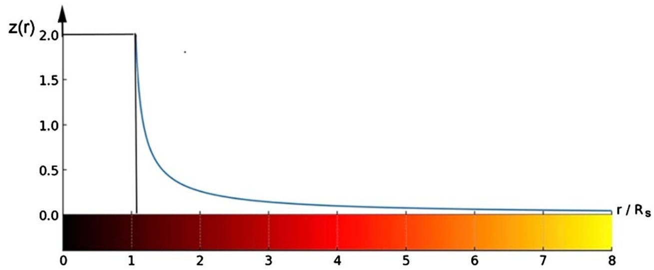

Figure 5. Schematic gravitational redshift as a function of distance.

However, there must be a source of radiation at a distance. The chromatic bar gives us the darkening towards the central part (which is not black). We can assume that the object is surrounded by plasma, which is emissive but whose temperature gradually decreases. This gives us another cause of reddening: the fact that the radiation temperature decreases. And we then have a change in wavelength according to:

$$\lambda_{obs} = \frac{b}{T(r)} \frac{1}{\sqrt{1 - \frac{R_s}{r}}} \tag{23}$$

By combining the two, we can then, very schematically, produce an image that matches the observational data (see **Figure 6**).

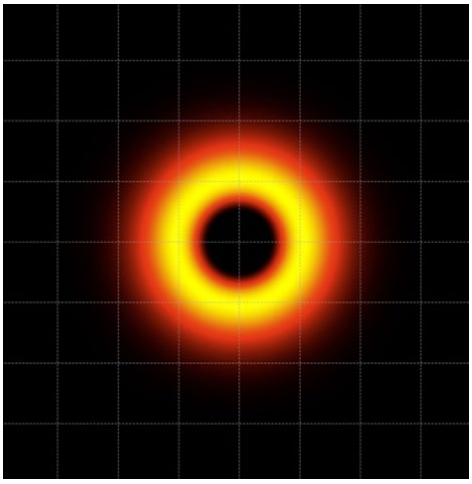

Figure 6. Schematic representation of a plugstar.

But until we have a coherent physical vision of the object, with density decreasing from the center to the edge and where magnetohydrodynamics undoubtedly plays a role, all this cannot be considered a model. It merely combines two phenomena that alter the wavelength: a gravitational redshift effect toward the center and a drop in radiation temperature toward the periphery, without specifying the mechanism of radiation emission. All this is, we admit, only a rough draft. Others will develop it further, younger people. We are old, and there is so much work to be done in this immense project that is the Janus Cosmological Model.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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