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Revisit of some Methods for Generating Compact Star Solutions in General Relativity: A Comparative Survey

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Abstract

Exact solutions of the Einstein field equations for static fluid spheres are important in the study of compact stars. However, it is often difficult to obtain solutions that are not only mathematically exact but also physically acceptable. In this review, we discuss five different analytical approaches that are commonly used to model static and spherically symmetric compact stars in general relativity. These include the Tolman-Oppenheimer-Volkoff TOV equation, the Schwarzschild interior solution with constant density, the Lake-Delgaty classification of exact perfect-fluid solutions, the Karmarkar embedding condition, and the minimal geometric deformation MGD method based on gravitational decoupling. For each approach, we explain the assumptions used to close the system of field equations and describe how the physical quantities are obtained. We also discuss the main physical features associated with each method. The Schwarzschild interior solution gives the well-known Buchdahl limit $R > 9M/4$, which places an important restriction on the maximum compactness of stellar objects. The Lake-Delgaty analysis shows that many exact mathematical solutions do not satisfy the basic physical requirements needed for realistic stars. The Karmarkar condition provides a useful relation between the metric potentials and has been widely applied in anisotropic stellar models, where the radial and tangential pressures are different. In comparison, the MGD approach separates the gravitational source into different sectors and allows known solutions to be extended by including additional matter fields or geometric corrections. To examine the physical acceptability of the models, we apply standard conditions such as the energy conditions, causality condition, Herrera cracking condition, and adiabatic stability criterion. The analysis shows that these requirements strongly restrict the set of physically meaningful solutions. This work provides a simple and organized overview of different exact methods used in compact star modeling and may serve as a useful reference for researchers working in general relativity and modified theories of gravity.

Keywords: Compact Stars; General Relativity; Tolman–Oppenheimer–Volkoff Equation; Karmarkar Condition; Minimal Geometric Deformation; Equation of State; Neutron Stars.

1. Introduction

Compact stars occupy a unique niche in modern astrophysics. Their central densities, reaching several times nuclear saturation density $\rho_0 \approx 2.3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$, place them beyond the reach of terrestrial accelerators, while the gravitational fields at their surfaces attain values where Newtonian gravity fails qualitatively. The interplay between extreme matter and curved spacetime makes them simultaneously laboratories for the equation of state EoS of cold dense matter and probes of strong-field general relativity [1, 2].

The theoretical study of compact stars begins with obtaining self-consistent interior spacetime solutions that match a vacuum Schwarzschild exterior across a well-defined stellar surface. This is a non-trivial task: the Einstein field equations for a spherically symmetric, static, perfect-fluid source reduce to a coupled system of ordinary differential equations in which three unknown functions appear but only two independent equations constrain them. Closure therefore requires an additional assumption — typically an EoS relating pressure p to energy density ρ, or a metric ansatz that renders the system analytically tractable.

Over the past eight decades a large catalogue of exact interior solutions has been assembled. However, not every exact solution represents a physically meaningful star. Conditions such as positive-definite and monotonically decreasing density and pressure profiles, subluminal sound speed, thermodynamic stability, and the absence of cracking instabilities must all be verified. The literature has consequently developed alongside a body of viability criteria that act as a decisive filter on the solution space [3, 4].

The multi-messenger era has added observational urgency to these theoretical considerations. Gravitational-wave detections by LIGO-Virgo, notably GW170817 [5], have placed constraints on the tidal deformability of neutron stars, while NICER X-ray timing has yielded simultaneous mass-radius measurements for PSR J0030+0451 and PSR J0740+6620. Any viable analytical model must be reconcilable with these data.

Compact stars are among the most important objects studied in modern astrophysics and gravitational physics. These stellar remnants are formed after ordinary stars consume their nuclear fuel and undergo gravitational collapse. Depending on the mass and internal composition, the final object may appear as a white dwarf, neutron star, or strange quark star. The matter inside such stars becomes extremely dense, far beyond the range where classical physics can give an accurate description. In neutron stars, for example, even a very small amount of matter carries an enormous mass because of the strong compression inside the star. Under these conditions, gravity becomes very strong and the Newtonian description of gravity is no longer sufficient. Therefore, general relativity provides the proper framework for studying the structure and physical properties of compact stars [1, 2]. For this reason, compact stars are often regarded as important astrophysical systems for examining the behavior of gravity in strong-field regions that cannot be reproduced in laboratory experiments on Earth.

Compact stars are not only important for the study of gravity, but they are also closely related to several unresolved problems in modern physics. The matter present inside neutron stars is still not fully understood. When the density becomes extremely high, $\rho_0 \approx 2.3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$, ordinary nuclear matter may change into other possible forms such as hyperonic matter, quark matter, or meson condensates [6]. The physical behavior of matter under such conditions is described through the equation of state, which relates the pressure and energy density inside the star. However, the exact form of this relation is still uncertain because these conditions cannot be reproduced directly in laboratory experiments. For this reason, observations of compact stars play an important role in understanding the properties of dense matter and provide useful information about particle physics at very high densities and energies. Recent simultaneous mass-radius measurements from the NICER telescope [7] and tidal deformability bounds from the gravitational-wave event GW170817 [5] have already ruled out several proposed EoS models, demonstrating how astrophysical data and microphysics are now tightly linked.

From a purely mathematical standpoint, finding exact interior solutions to the Einstein field equations for a self-gravitating fluid sphere is a non-trivial problem. The field equations for a static, spherically symmetric perfect fluid reduce to the Tolman–Oppenheimer–Volkoff (TOV) equation [2, 1], a coupled system in which the number of unknown functions exceeds the number of independent equations. Closing this system requires an additional physical or geometric input, and the search for such closures — through prescribed equations of state, metric ansätze, or geometric constraints such as the Karmarkar condition [8] — has motivated a large body of work over the past eight decades. Not all exact solutions, however, describe physically reasonable stars. A solution must satisfy strict conditions: the density and pressure must be positive and decrease monotonically from the centre to the surface, the sound speed must remain below the speed of light, and the star must be stable against small perturbations [3, 4]. The fact that the vast majority of known exact solutions fail at least one of these tests [3] shows that finding a physically acceptable solution is genuinely difficult. This difficulty is itself a motivation: each new exact solution that passes all viability tests adds a concrete, analytically controlled data point to our theoretical map of what relativistic compact stars can look like. Such solutions are valuable starting points for numerical simulations, for testing modified gravity theories, and for building intuition about how matter and geometry are coupled in the strong-field regime.

This paper organises the most widely employed analytical construction methods into a coherent narrative. Section 2 establishes the TOV framework. Sections 3–6 treat, respectively, the classical Schwarzschild interior solution, the Lake–Delgaty systematic approach, the Karmarkar embedding technique, and gravitational decoupling via MGD. Section 7 summarises the physical viability tests applicable to any candidate solution, and Section 9 offers concluding remarks.

2. The Tolman–Oppenheimer–Volkoff Framework

The starting point for every static, spherically symmetric stellar model in GR is the line element

$$\mathrm{d}s^2 = -\mathrm{e}^{2\nu(r)}\mathrm{d}t^2 + \mathrm{e}^{2\lambda(r)}\mathrm{d}r^2 + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right), \tag{1}$$

where $\nu(r)$ and $\lambda(r)$ are metric potentials to be determined. For a perfect-fluid energy-momentum tensor $T^{\mu\nu} = (\rho + p)u^\mu u^\nu + p\,g^{\mu\nu}$, the Einstein field equations $G^{\mu\nu} = 8\pi G\,T^{\mu\nu}$ (with $c = 1$) yield three independent components:

$$\begin{aligned} \mathrm{e}^{-2\lambda}\left(2r\lambda' - 1\right) + 1 &= 8\pi r^2\rho, && (2)\\ \mathrm{e}^{-2\lambda}\left(2r\nu' + 1\right) - 1 &= 8\pi r^2 p, && (3)\\ p' &= -(\rho + p)\,\nu', && (4) \end{aligned}$$

where primes denote $\mathrm{d}/\mathrm{d}r$. Introducing the interior mass function

$$m(r) = \frac{r}{2}\left(1 - \mathrm{e}^{-2\lambda}\right), \tag{5}$$

equation (4) is recast as the celebrated TOV equation [1, 2]:

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{(\rho + p)\left[m(r) + 4\pi r^3 p\right]}{r[r - 2m(r)]}. \tag{6}$$

Equation (6) governs hydrostatic equilibrium in curved spacetime. Its Newtonian limit reproduces the familiar equation of hydrostatic support, but the relativistic corrections — the appearance of p alongside ρ in the numerator and the factor $(r - 2m)$ in the denominator — become decisive near the Schwarzschild radius $r_s = 2GM/c^2$.

The system is closed by specifying an EoS $p = p(\rho)$. Numerical integration of Eq. (6) proceeds from the centre with boundary conditions $\rho(0) = \rho_c$ and $m(0) = 0$ outward to the surface defined by $p(R) = 0$, from which the total gravitational mass $M = m(R)$ is read off. The Darmois–Israel junction conditions then require continuity of the induced metric and the extrinsic curvature at $r = R$, matching the interior solution to the exterior Schwarzschild spacetime.

3. Schwarzschild's Uniform-Density Interior Solution

The oldest exact interior solution, due to Schwarzschild [9], assumes uniform density $\rho = \rho_0 = \mathrm{const.}$ Although physically idealised real stars possess density gradients, this solution is analytically transparent and historically important as the first demonstration that GR imposes an absolute upper limit on stellar compactness.

Under the incompressibility assumption the mass function reduces to $m(r) = \frac{4\pi}{3}\rho_0 r^3$, and the radial metric potential $\mathrm{e}^{-2\lambda} = 1 - (2M/R)(r^2/R^2)$ follows immediately. Substituting into the TOV equation and integrating yields the pressure profile:

$$p(r) = \rho_0 \frac{\sqrt{1 - 2Mr^2/R^3} - \sqrt{1 - 2M/R}}{3\sqrt{1 - 2M/R} - \sqrt{1 - 2Mr^2/R^3}}. \tag{7}$$

The central pressure $p(0)$ diverges when the denominator of Eq. (7) vanishes. Setting the denominator to zero and solving for the compactness gives the celebrated *Buchdahl bound* [10]:

$$\frac{2M}{R} < \frac{8}{9}, \qquad \text{equivalently} \quad R > \frac{9}{4}M. \tag{8}$$

This inequality is independent of the EoS and applies to any static, spherically symmetric perfect-fluid configuration. The uniform-density solution saturates this universal bound and thereby establishes it rigorously, even though a truly incompressible fluid propagates acoustic perturbations at infinite speed; a violation of causality that renders the model physically inadmissible as a description of real matter.

4. The Lake-Delgaty Classification Approach

A systematic attempt to catalogue all physically reasonable exact perfect-fluid solutions was undertaken by Lake and Delgaty [3]. Their approach inverts the conventional logic: rather than prescribing an EoS and solving for the metric, one chooses one metric potential freely and derives the remaining unknowns from the field equations.

Selecting $\mathrm{e}^{2\nu} = f(r)$ as the free function, the field equations determine $\mathrm{e}^{2\lambda}$ and subsequently ρ and p. Compatibility of the two pressure equations then yields the *pressure isotropy condition* [11], a second-order linear ODE in $\mathrm{e}^{2\nu}$:

$$\begin{aligned} &2r\left(1 - \mathrm{e}^{-2\lambda}\right)\nu'' + \Big[r^2\left(\nu'^2 + \tfrac{1}{2}\nu''\right) \\ &-r\nu' - \mathrm{e}^{-2\lambda}\left(r\nu' + 1\right) + 1\Big] = 0. \end{aligned} \tag{9}$$

Lake and Delgaty subjected every known solution to a minimal viability filter:

1. regularity at the centre (ν, λ, ρ, p all finite),
2. positive-definite density and pressure throughout,
3. monotonic decrease of ρ and p with increasing r, and
4. positive surface energy density at $r = R$.

Of the 127 distinct solutions examined, only 16 satisfied all four criteria simultaneously. This striking outcome demonstrates how stringent the viability filter is: the overwhelming majority of mathematically exact solutions have no physical relevance.

The Lake–Delgaty work also introduced a systematic parametrisation in terms of *generating functions*. For instance, the choice $\mathrm{e}^{2\nu} = (1 + ar^2)^n$ with integer n produces the Durgapal family [11], several members of which survive the viability filter. This prefigures later approaches that treat the seed metric itself as the primary design variable.

5. The Karmarkar Embedding Technique

A geometrically motivated class of solutions emerges from the theory of isometric embeddings. A four-dimensional Riemannian manifold belongs to *embedding class one* if it can be isometrically embedded in a five-dimensional flat (Euclidean or Minkowskian) space. Karmarkar [8] derived the necessary and sufficient condition for a static, spherically symmetric spacetime to satisfy this property:

$$R_{1414}\,R_{2323} = R_{1212}\,R_{3434} + R_{1224}\,R_{1334}, \tag{10}$$

where R_{ijkl} are components of the Riemann curvature tensor. For the metric (1), condition (10) reduces to a single ODE linking the two metric potentials [12]:

$$2\nu'' + 2\nu'^2 - \lambda'\nu' = \frac{\nu'\lambda'\,\mathrm{e}^{2\lambda}}{\mathrm{e}^{2\lambda}-1}. \tag{11}$$

Equation (11) makes it possible to specify the metric potential $\nu(r)$ in advance and subsequently determine $\lambda(r)$, thereby reducing the problem from two independent metric functions to a single-potential formulation. The standard procedure may be summarized as follows:

1. Select a physically reasonable expression for $\nu(r)$. Polynomial or rational forms in r^2 are commonly adopted since they ensure regular behavior near the stellar center.
2. Integrate Eq. (11) to derive the corresponding form of $\mathrm{e}^{2\lambda(r)}$.
3. Insert the obtained metric functions into Eqs. (2)–(3) in order to evaluate the matter variables $\rho(r)$ and $p(r)$. In this approach, the EoS is obtained implicitly through a parametric relation.
4. Apply the boundary requirement $p(R) = 0$ at the stellar surface to determine the remaining constants of integration or model parameters.

This approach has been widely employed in the study of *anisotropic* compact stars, where the radial and tangential pressures satisfy $p_r \neq p_t$. In such configurations, the anisotropy factor $\Delta = p_t - p_r$ introduces an additional unknown into the system. The Karmarkar condition supplies the extra geometric relation necessary to close the field equations without assuming a specific EoS [13]. Nevertheless, the condition itself is entirely geometric in nature and does not encode any thermodynamic information. Consequently, physical acceptability requirements, including stability conditions and energy criteria, must be verified separately after obtaining the solution.

6. Gravitational Decoupling via Minimal Geometric Deformation

A more recent and highly flexible approach is provided by the minimal geometric deformation MGD method within the framework of gravitational decoupling, originally developed by Ovalle [14]. The main concept of this technique is to separate a complicated energy–momentum tensor into simpler constituent sectors, each of which can be treated independently before combining the resulting solutions into a complete gravitational configuration.

Starting from a known perfect-fluid solution $\{\bar{\nu}, \bar{\lambda}, \bar{\rho}, \bar{p}\}$ — the *seed* — one introduces an additional source $\theta^{\mu\nu}$ coupled to the gravitational sector with dimensionless strength α:

$$T^{\mu\nu}_{\text{total}} = T^{\mu\nu}_{\text{seed}} + \alpha\,\theta^{\mu\nu}. \tag{12}$$

Under a purely radial deformation, only the radial component of the metric is modified:

$$\mathrm{e}^{-2\lambda(r)} \;\longrightarrow\; \mathrm{e}^{-2\bar{\lambda}(r)} + \alpha\,h(r), \tag{13}$$

while the temporal potential ν is held fixed at its seed value. Substituting (13) into the full field equations, the system *decouples* into two independent sub-systems: one that recovers the seed equations identically, and one governing the deformation function $h(r)$:

$$\begin{aligned} h' - \frac{2}{r}\left(1 - r\,\bar{\lambda}'\right) h \quad &= \quad -16\pi r\,\theta^{r}_{\ r} + \frac{2}{r}\left(1 - \mathrm{e}^{-2\bar{\lambda}}\right)\left(1 + r\bar{\nu}'\right) \\ &- \quad r\bar{\nu}'^{\,2} - r\bar{\nu}''\,, \end{aligned} \tag{14}$$

which is a first-order linear ODE and is therefore far easier to solve than the original coupled system. Once $h(r)$ is determined — either by choosing $\theta^{\mu\nu}$ explicitly (a physical closure) or by prescribing a geometric condition on h — the full solution is assembled by superposition.

The junction conditions at the stellar surface impose an algebraic constraint on $h(R)$ relating the surface deformation to the compactness M/R [15]. The physical interpretation of $\theta^{\mu\nu}$ is broad: it may represent an anisotropic fluid, a dark matter distribution, a scalar field, or quantum corrections to the classical fluid. This flexibility makes MGD a unifying framework. As demonstrated by Ovalle and collaborators, starting from the Tolman IV seed and applying the MGD extension yields anisotropic compact-star models consistent with the observed mass-radius range of neutron stars [15].

An extended variant, "the *complete geometric deformation* (CGD)" deforms both metric potentials simultaneously. In the CGD scheme two additional closure conditions are required, making the procedure more involved but also applicable when the extra source interacts with the vacuum exterior and modifies the geometry beyond pure Schwarzschild.

7. Physical Viability Criteria

Irrespective of the construction method, any candidate stellar solution must pass a standard battery of physical tests before it can be considered astrophysically meaningful.

7.1. Regularity and Matching Conditions

The metric potentials must be regular throughout $0 \le r \le R$: finite, positive, and at least twice differentiable. In particular, $m(0) = 0$, $\mathrm{e}^{2\nu(0)}$ and $\mathrm{e}^{2\lambda(0)}$ must be finite and positive, and both ρ and p must attain their maxima at the centre. At the stellar surface the Darmois–Israel junction conditions require continuity of the induced metric and the extrinsic curvature, yielding $p(R) = 0$ and the identification $M = m(R)$.

7.2. Energy Conditions

The weak energy condition (WEC) demands

$$\rho \ge 0, \qquad \rho + p \ge 0, \tag{15}$$

everywhere inside the star. The strong energy condition (SEC) adds $\rho + 3p \ge 0$, while the dominant energy condition (DEC) requires $|p| \le \rho$. For anisotropic models these conditions are applied to both the radial pressure p_r and the tangential pressure p_t componentwise.

7.3. Causality and the Herrera Cracking Condition

The adiabatic sound speeds in the radial and tangential directions are

$$v_r^2 = \frac{\mathrm{d}p_r}{\mathrm{d}\rho}, \qquad v_t^2 = \frac{\mathrm{d}p_t}{\mathrm{d}\rho}. \tag{16}$$

Causality demands $0 \le v_r^2 \le 1$ and $0 \le v_t^2 \le 1$ throughout the star. For anisotropic models Herrera's cracking condition [4] further requires that the sign of $v_t^2 - v_r^2$ does not change inside the star, a sign reversal indicating a cracking instability. The Abreu–Hernandez–Nuñez criterion [16] tightens this requirement to

$$-1 \;\le\; v_t^2 - v_r^2 \;\le\; 0. \tag{17}$$

7.4. Stability Under Radial Perturbations

A stellar model is stable against radial perturbations only if [17]

$$\frac{\mathrm{d}M}{\mathrm{d}\rho_c} > 0, \tag{18}$$

where ρ_c is the central density. Points in the M–ρ_c diagram where $\mathrm{d}M/\mathrm{d}\rho_c = 0$ signal the onset of instability. Equivalently, the adiabatic index

$$\Gamma = \frac{\rho + p}{p}\frac{\mathrm{d}p}{\mathrm{d}\rho} \tag{19}$$

must satisfy $\Gamma > 4/3$ throughout the interior, generalising the classical Lane–Emden stability criterion; relativistic corrections shift the threshold upward by terms of order M/R.

7.5. Compactness Bound

As established in Section 3, the Buchdahl bound (8) sets the maximum compactness for any static perfect-fluid star. Observationally, NICER mass-radius measurements and the tidal deformability constraint from GW170817 [5] provide empirical targets in the M–R plane. A physically viable analytical model must reproduce the observed population of neutron stars within current measurement uncertainties, typically $M \sim 1.4$–$2.1\, M_\odot$ and $R \sim 10$–$14\,\mathrm{km}$.

8. Discussion

The four methods surveyed above span a spectrum from direct physical prescription to pure geometric constraint. The TOV framework with a specified EoS is the most physically transparent: every ingredient has a clear thermodynamic meaning, and the integration is straightforward once $p(\rho)$ is known. Its weakness is that realistic nuclear EoSs are available only in tabulated form, and analytical insight is limited.

The Schwarzschild interior and the Lake–Delgaty approach occupy the opposite extreme: they begin with metric ansatze and extract the implied physics, gaining analytical transparency at the cost of a priori physical motivation. The Karmarkar condition occupies an intermediate position: the geometric constraint is well-defined and imposes a non-trivial algebraic relation between the metric potentials, yet the resulting EoS still lacks a microphysical derivation.

Gravitational decoupling via MGD is arguably the most powerful tool available today. By treating the problem perturbatively in α, it preserves the entire body of known exact solutions as seeds and extends each of them into a richer family. The superposition structure makes it straightforward to include physically motivated additional sources — anisotropy, dark matter, scalar hair and the decoupled first-order equation for $h(r)$ is typically integrable in closed form.

A practical consideration worth noting is that all four methods share a common dependence on spherical symmetry and staticity. Extensions to rotating compact stars require the Hartle-Thorne perturbative framework or fully numerical methods (e.g., the LORENE or RNS codes). Rotation introduces oblateness and a frame-dragging potential $\omega(r, \theta)$, breaking the clean separation of the field equations that makes the static, spherically symmetric problem analytically tractable. Analogous decoupling schemes for rotating backgrounds are an active area of current research.

9. Conclusions

We have presented a concise but technically complete survey of the principal methods for constructing compact star solutions in general relativity. The main findings may be summarised as follows.

- The TOV equation (6) is the basic equilibrium condition for any static, spherically symmetric star in general relativity. Every solution built by other methods — whether through a metric ansatz, a geometric constraint, or a decoupling scheme — must reduce to the TOV predictions when the same closure is applied. This is a useful internal check on any new model.
- Setting the density constant in the Schwarzschild interior problem leads directly to the Buchdahl bound $R > 9M/4$. Incompressible matter is not realistic, of course, but the bound itself is not tied to that assumption — it holds for any static perfect-fluid star regardless of the EoS. For this reason it remains a hard constraint that all acceptable stellar models must satisfy.
- Of the 127 exact perfect-fluid solutions tested by Lake and Delgaty [3], only 16 passed even a basic set of physical checks. This is a striking number. It tells us that writing down an exact solution to the Einstein equations is not the hard part; the hard part is ensuring that the density and pressure behave sensibly, that the sound speed stays below the speed of light, and that the star is actually stable. Most exact solutions fail on at least one of these counts.
- The Karmarkar embedding condition simplifies the closure problem by reducing it to a single differential equation connecting the metric potentials. This method has been particularly effective in constructing anisotropic compact-star solutions.
- Gravitational decoupling through the MGD framework represents one of the most adaptable modern approaches. Beginning with a known seed solution, the method allows the generation of extended stellar configurations with additional matter sources or geometric corrections introduced in a controlled manner.

In all of these approaches, physical acceptability conditions including the energy conditions, causality requirement, Herrera cracking criterion, and the Buchdahl compactness bound play a central role in determining the validity of a stellar model. A solution may be mathematically consistent, yet it cannot represent a realistic compact object if any of these conditions are violated. Future investigations are expected to combine these theoretical frameworks with increasingly realistic nuclear EoS models derived from chiral effective field theory and perturbative QCD, while also confronting them with rapidly growing observational evidence from multi-messenger astronomy, such as advanced gravitational-wave detectors and next-generation X-ray missions.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Data Availability

The data used in this study are available from the corresponding author upon reasonable request.

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