A Remark on "A Non-Interacting Low Mass Blackhole-Giant Star Binary System": Companion Most Likely be a 'Triaxial Star'

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Abstract: ***Thompson et al (2019) detected an unseen companion of the red-giant star 2MASS J05215658 +4359220 and interpreted this companion candidate as most likely a black hole. Reanalyzing the observational parameters van den Heuvel and Tauris (2020) concluded that the unseen companion might "not be a black hole "but it can be a close binary consisting of two main sequence stars of ~ 0.9 M⊙each. Further refining the observed data Thomas et al (2020) argued the nature of the companion in favor of black hole candidate. Based on numerical simulation's results and the detection super-luminous supernova ASASSN-15LH this author propose this unseen companion most likely be a 'Triaxial Quark Star' or simply a "Triaxial Star". The significant impacts are discussed.***

Keywords: Gravitational Waves, Binary System, Quark Star, Compact Object

1. Introduction

Combining radial velocity and photometric variability data Thompson et al (2019) in their study showed that the bright, rapidly rotating giant star 2MASS J05215658 + 4359220 is a black hole binary system with the unseen companion which has mass = $3.3\ ^{+2.8}_{-0.7} M_\odot$. Regarding identification of this companion they first suspected that it is either a non-interacting low mass black hole or an unexpectedly massive neutron star.

Studies of compact object population of massive star binary systems (Kobulnicky et al 2014) hint that more massive (> 10 $M_\odot$) 'primary' components ultimately produce neutron stars and black holes while broad distribution of secondary (i.e., companion) components and orbital period suggest many massive stars can have low masses, long-lived companions. The existence of such systems have been proposed earlier (Gureinov&Zel'dovich1966; Trimble & Thorne 1969) but not yet found.

For understanding the nature and properties of such systems Thomspon et al (2019) searched for stellar binaries with massive unseen companions using the observed data available in APOGEE experiment (e.g., Apoche Point Observatory Galactic Evolution Experiment). Analysis of the radial velocity measurement data from APOGEE clearly indicated the presence of required systems they are searching for. But problem was in determining the mass of the companion of that system which remains unsettled. Because the parameters like the orbital period, inclination, and eccentricities of this system was unknown.

As an alternate, they used results of the periodic variations in photometric data available in the All Sky Automated Survey for Supernovae (ASASSN) (Shappee et al 2014; Kochanek et al 2017). They identified the giant star 2MASS J05215658 + 4359220 which is a binary exhibiting the following properties:

Acceleration ≈ 2.9 km $s^{-1}.day^{-1}$
Orbital Period = 83.2 ±0.06 days
Radial velocity semi-amplitude K = 44.6 ±0.1 km s^{-1}
Eccentricity (e) = 0.0048 ±0.0026
Companion mass $M_{comp} = 3.3^{+2.8}_{-0.7} M_\odot$

The mass of the compact companion falls in the mass-gap range (2 – 5) $M_\odot$ between neutron stars and black holes (Farr et al 2011) i.e., the highest neutron star mass and the lowest black hole mass. The maximum mass of neutron star is not yet settled to-date. The highest mass observed so far is $2.14\ ^{+0.10}_{-0.09} M_\odot$ (in the case of PSR J0740+6620 (Cromartie et al 2019) and the predicted theoretical maximum masses of neutron stars are ≅ 2.5 $M_\odot$ (Lattimer 2012), 3.2 $M_\odot$ (Rhodes &Ruffini 1974). The well measured value of the lowest black hole mass is 5 $M_\odot$ (Ozel et al 2010; Farr et al 2011) and the estimated or predicted lower limit of black hole masses may be 2.3 $M_\odot$ (Heida et al 2017) and 2.7 $M_\odot$(Orosz et al 1988) in the cases of X-ray binaries GX 339– 4, and 4U 1543– 47, respectively. As a result, Thompson et al (2019) proposed that the invisible companion mass of the red giant binary system 2MASS J05215658 + 4359220 most likely be a black hole with the lowest mass.

The invisible companion mass of $3.3\ ^{+2.8}_{-0.7} M_\odot$ has been reanalyzed by van den Heuvel and Tauris (2020) in two ways:

a) If the companion were a close binary, then the mass of each component of the binary would be ~ 1.65 $M_\odot$ and that would have been detectable in the spectral energy distribution (SED) of the red-giant. In that case, black hole is the only remaining possibility.
b) If the red-giant star 2MASS J05215658 + 4359220 is a triple star system, then the unseen companion is ≥ 1.8 $M_\odot$ i.e., the companion could be a very close binary of two main sequence stars each with ~ 0.9 $M_\odot$ mass. Applying the properties of a 1 $M_\odot$ red giant with a close binary companion such as generation of detectable light, x-ray emission, high [C/N] abundant ratio, van den Heuvel and Tauris (2020) concluded that the unseen

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companion of 2MASS J05215658 + 4359220 is definitely "not a black hole" due to the observation of insufficient x-ray emission and [C/N] ratio and also of unusual black hole mass.

Further refining the basis of arguments (i.e., x-ray emission, C/N ratio and unusual mass) made by van den Heuvel and Tauris (2020) for favoring "not to be a black hole" Thompson et al (2020) re-concluded that the companion of 2MASS J05215658 + 4359220 may be black hole candidate.

The discovery of a 3M⊙ dark companion in the red-giant V723 (Jayasinghe et al 2021) offered a significant contribution in determining the nature of the companion compact object in a red-giant binary. The observed parameters of this red-giant are:
Type: A luminous red-giant located in the Monoceros Constellation and classified as a long period variable star.

Period (P_{orbit}) = (nearly circular orbit) 59.9363 ± 0.0016 days
Eccentricity (e) = 0.0150 ± 0.0009
Temperature ($T_{eff,\ giant}$) ≈ 4440 K
Luminosity L_{giant}≈ 173 L⊙
Mass function (high) f(M) = 1.72± 0.01M⊙
Companion mass M_{comp} = 3.04 ± 0.06 M⊙

Using the observed parameters and the radial velocity curve associated with the second component having unusual in structure compared to any other system and also a triple system Jayasinghe et al (2021) estimated the mass function
$f(M) = P_{orb}K^3 (1 - e^2)^{3/2} / 2\pi G$
$= M^3_{comp}\ Sin^3 i / (M_{giant} + M_{comp})^2 \approx 1.73 M_\odot$
With P_{orb}= 59.9363d, e = 0.015, K= 65.45 $km.s^{-1}$.

The most striking feature of this large mass function is that the observed giant star V723 Mon has a massive companion with a minimum mass M_{comp}≈3 M⊙. This implies that V723 Mon is a prime candidate identifying as a non-interacting, compact object binary and the massive companion is a "single compact object**",** most likely a black hole in the **'**mass –gap'.

If we consider the above results and impose on the first low mass black hole companion of the red-giant 2MASS J05215658 + 4359220 then the simplest explanation for massive companion suggests that the companion is most likely a black hole candidate which support the hypothesis of Thompson et al (2019) but disagree with the conclusion of van den Heuvel and Tauris(2020) i.e., "not to be a black hole" as well as "binary companion". This hints the companion of the red-giant binary 2MASS J05215658 + 4359220 possibly be "a new type of compact object".

Triaxial instability (i.e., triplanar symmetry w.r.t. three orthogonal x, y, z planes) has an important role for both neutron stars (NSs) and quark stars (QSs). As the quark matter is composed of deconfined quarks (i.e., 'u' (up), 'd' (down) and 's' (strange) quarks) so quark clustering is another important parameter for bifurcation from the axis symmetry to the triaxial configuration. Although this bifurcation is very close to the mass shedding limit but for soft neutron star equation of state with large compactness the triaxial sequence could totally disappear (or vanish). According to general relativity, the quark stars, in general, can have larger triaxial deformation (e.g., R_y / R_x ratio) before terminating the sequence at the mass shedding limit. As the decomposed 'u', 'd' and 's' quarks could be stable Bodmer 1971; Witten 1984) the significance of triaxial deformation is that a small tidal deformability of quark star is favorable for detection through observation (Lai et al 2018; Dai et al 2016). Using new equation of state, based on quark clustering proposed by Lai and XU (Lai &Xu 2018), Zhou et al (2018) showed in a numerical simulation study that in a stiff equation of state a triaxial quark star can support its maximum allowed mass up to 3.3 M⊙. Comparing solution sequences of quark stars with of neutron star they found three significant results in their study:

1) Quark stars have a longer triaxial sequence of solution, in general, than neutron stars. This means that quark stars can reach a larger triaxial deformation before terminating the sequence at the mass shedding limit;
2) For the similar triaxial situation quark stars are (slightly) more efficient gravitational wave sources than the neutron stars;
3) Triaxial supermassive solutions can be found for quark stars implying that quarks stars can possess higher maximum masses than that of the neutron stars.

In this context, the detection of super-luminous supernova ASASSN-15LH provides a valuable information of possible signature of the birth of a strange quark star (Parui 2023).

Keeping in view of the above results, this author concludes that the unseen companion compact object with mass 3.3 M⊙ in the red-giant binary 2MASS J05215658 + 4359220 is a triaxially deformed quark star or simply a triaxial star (Parui 2023; Parui 2023a) in the form of quark star.

The significant impacts are:

1) The companion of the binary system 2MASS J05215658 + 4359220 detected in 2019 but since then it's identification oscillates either a black hole or a main sequence binary with mass ~ 0.9 M⊙ each.
2) Numerical simulation study by Zhou et al (2018) showed that stiff EOS can support the maximum mass upto 3.3 M⊙. Based on this I concluded that the companion is neither a black hole nor a binary, rather it is a new type compact star, called Triaxial Strange Star or simply triaxial star.in the form quark star. It will dissolve the companion identification problem.
3) It reduces the mass gap range from (2 - 5) M⊙ to (3.3 - 5) M⊙.
4) This provides the first evidence of formation of a triaxial star as well as strange quark star i.e., quark star, in a binary star.
5) This will be the highest mass of the physically existing compact star in the mass gap ladder (Parui 2023b).
6) The first evidence of the existence of a real triaxial star i.e. evidence of physically existing triaxial star and also of strange quark star.

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