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LETTERS

The nature of the companion of PSR J1719–1438: a white dwarf or an exotic object?

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Abstract We raise the possibility that the very dense, compact companion of PSR J1719–1438, which has a Jupiter-like mass, is an exotic quark object rather than a light helium or carbon white dwarf. The exotic hypothesis naturally explains some of the observed features, and provides quite strong predictions for this system, to be confirmed or refuted in feasible future studies.

Key words: binary pulsars — exotic matter — pulsars: individual (PSR J1719–1438)

1 INTRODUCTION

The presence of bodies orbiting pulsars (planets) was quite unexpected before their discovery by Wolszczan & Frail (1992), and prompted ample discussion about their formation scenarios (Podsiadlowski 1993). Overall, the fraction of pulsars with planets does not currently seem very large, suggesting special conditions for their formation, rather than a generic channel yielding a large number of pulsar-planet systems. A recent work (Bailes et al. 2011), however, added an important twist to this problem: the detection of a Jupiter-mass object around the pulsar PSR J1719–1438, a 5.7 ms pulsar. This has been interpreted as a case in which an ultra low-mass X-ray binary suffered a transformation of a white dwarf into a planet. Moreover, this downsizing suggests, to comply with the condition of the companion radius fitting inside the Roche Lobe (estimated to be smaller than 4.2×10^4 km for the most favorable parameters), a heavier-than-helium composition of the latter. An important corollary of the study is the existence of a *minimum density* for the companion object, a direct consequence of the orbital period and Roche Lobe considerations (Bailes et al. 2011), namely

$$\rho = \frac{3\pi}{(0.462)^3 G P^2} \geq 23\,\mathrm{g\,cm^{-3}}\,. \tag{1}$$

This average is far in excess of the density of normal Jupiter-sized planets and prompted the evaporated helium/carbon white dwarf picture (in fact a helium object would be contrived, but is not impossible because of size constraints (Benvenuto et al. 2012).

Our main argument is that the existence of the lower bound, Equation (1), allows an alternative interpretation in terms of exotic matter, namely versions of stable or metastable quark matter, discussed over the last decades (Witten 1984; Alcock et al. 1986; Glendenning et al. 1995; Michel 1988). As suggested below, this is a sound alternative, even if not yet compelling, and would have, if confirmed, deep implications for the nature of dense matter. We point out and discuss the sketch and a few direct consequences of this hypothesis in the remainder of this Letter.

2 VARIANTS OF QUARK MATTER COMPOSITION FOR THE COMPANION OBJECT

The simplest possible candidate of an exotic object for the companion of PSR J1719–1438 is a nugget of superdense strange quark matter (SQM) with planetary mass (Witten 1984; Alcock et al. 1986). These chunks of cold SQM can hypothetically exist all the way down to microscopic masses (referred to as *strangelets*), with densities $\sim 4B \sim 4 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ in the limit in which gravitational forces are not important. In fact, a nugget with the mass of $\sim$ Jupiter could *not* have formed in the early Universe because of the horizon constraints (Witten 1984), even if the SQM hypothesis is true. However, the ejection of a planetary mass nugget is quite possible in astrophysical events (see below). The radius of a nugget with Jupiter's mass is just ≈ 1 km, and easily satisfies all observational constraints.

While the SQM nugget is homogeneous by construction, the possible existence of *structured*, symmetric quark states at low baryon number A has been considered in the past, leading to a different type of matter in macroscopic astrophysical objects. The calculations of the so-called H dibaryon (a quark analog to a $\Lambda - \Lambda$ state) led to the suggestion of its (meta)stability (Jaffe 1977), recently reinforced by lattice QCD calculations (Inoue et al. 2011), although it has yet to be found in experiments. A novel state, the H-matter (Tamagaki 1991), which is conceptually analogous to neutron matter, would appear, which is especially interesting in the case of a stable dihyperon but also relevant for the metastable case. It is interesting to note that this proposal has been recently revived by Lai et al. (2011) and by Occam's razor, which points toward a common composition for the pulsar and its companion. A still bolder proposal is the completely symmetric 18-quark state, originally termed Q_α because of the suggested analogy with the helium nucleus (Michel 1988). There is no experimental evidence for its presence, and only very rough estimations of the binding energy of this state, $(uds)^6$ with $A = 6$ and $S = -6$, are available, which may be stable even if the H particle is *not* bound with respect to the $\Lambda\Lambda$ threshold (Shanahan et al. 2011).

The structure of macroscopic pure H-matter and Q_α objects has not been fully addressed (however, see Benvenuto et al. (1990) for the possible role of the latter in compact stars). Since Q_αs are a spin-0 uncharged state, it is quite natural to treat them as bosons with a repulsive (hardcore-like) interaction. A phenomenological description of self-interacting bosons applied to stellar structure was first discussed in Colpi et al. (1986). Further work (Donoghue & Sateesh 1988) derived an effective equation of state in the low-density and high-density limits specific to a scalar diquark with mass $\sim 575\ \mathrm{MeV}$. These results can be readily adapted for the symmetric strangelet case, like the 18-quark Q_α (Michel 1988) by appropriately changing the mass and coupling constant values, giving a maximum mass for a stellar model of

$$M_{\max} = 0.03 \left(\frac{\lambda}{25}\right)^{1/2} \left(\frac{6\mathrm{GeV}}{m_A}\right)^2 M_\odot\,. \tag{2}$$

This mass is comfortably within the required range unless the mass of the lightest bosonic strangelet is much heavier, but rather insensitive to the exact value of the self-interaction parameter λ, which remains poorly determined. However, the radius is still orders of magnitude smaller than the ones calculated in the recent proposal of strangelet dwarfs by Alford et al. (2011), in which the radius is determined by electrostatic forces. Because of the charge of the considered strangelets, the latter is in the ballpark of more "normal" white dwarfs, and quite insensitive to the exact mass. The same happens with the former proposal of strange dwarfs by Glendenning et al. (1995). The point of these rough estimates is to remark that an exotic Jupiter mass object with could be very different in size, truly point-like indeed, and thus easier to fit within the observed features.

3 FORMATION MECHANISMS FOR THE SYSTEM

It is clear from the outset that the exotic nature of the companion would force researchers to consider the nature of a strange star acting as a pulsar (Benvenuto et al. 1990; Jaikumar et al. 2006), and therefore opens the possibility for a common origin of both objects. Among the possible common origin scenarios, we should remark that the so-called fallback model (Podsiadlowski 1993) for the formation of planets around pulsars must be *extended* in this case to consider material ejected by the formation of the compact star itself. This leads back to the idea of an SQM driven explosion (Benvenuto & Horvath 1989), in which the conversion process $n \rightarrow uds + energy$ is inevitably turbulent (Horvath & Benvenuto 1988; Benvenuto & Horvath 1989; Horvath 2010), a proposal recently confirmed by direct numerical calculations (Herzog & Röpke 2011), setting the stage for the ejection of exotic matter as an effect of large turbulent, high-velocity eddies. The companion would form out of this ejected matter, as a result of rapid rotation.

Another possibility for the formation of the PSR J1719–1438 system is the merging of two low-mass strange stars, recently shown by Bauswein et al. (2009) to eject up to $0.03\ M_{\odot}$ or an order of magnitude more matter than needed, which would be acceptable provided the sum of both initial masses does not exceed the limiting mass of the strange star sequence (note that a naive balance of tidal torques and surface tension of one nugget had a predicted mass of $\sim 10^{-18} M_{\odot}$ (Madsen 2001), thus leading to an enormous number of asteroid-sized nuggets instead).

Last, but not least, we would like to point out that a third scenario, the merging of two white dwarfs (Podsiadlowski 1993), which leads to the so-called Accretion-Induced-Collapse (AIC) forming a single “neutron” star, should necessarily be revisited concerning the formation of SQM. This is because the microscopic conditions for SQM formation would be achieved anyway when supranuclear densities are achieved and, therefore, in addition to being an attractive channel for the direct formation of a millisecond pulsar, the scenario would have the bonus feature of providing some *exotic* ejected matter as well, yet to be calculated and quantified. Indeed, it is quite unlikely to make a neutron star without also converting it to a strange star in the same process of AIC.

4 CONCLUSIONS

We have argued in this Letter that an exotic object is viable as a companion of the millisecond pulsar PSR J1719–1438, and in fact is a unique alternative to a helium/carbon white dwarf. To distinguish both cases, there are a few theoretical scenarios to be explored in detail, and some key observations worth performing. A similar idea (namely, an exotic composition) was formerly advanced by Xu & Wu (2003) for the case of Wolczan’s planets, for which less information is available even today. If the companion of PSR J1719–1438 is an exotic object, it would easily explain why there are no observed eclipses in spite of a (nearly) edge-on inclination. Actually, the strong photometric limits derived by Bailes et al. (2011) using the Keck-LRIS instrument cannot be used to place constraints on the inclination either. In the cases of an SQM nugget or structured strangelet, the size would be too small to detect any photometric signal, but if a strangelet dwarf is realized, its size would be $\sim 5 \times 10^3$ km (Alford et al. 2011), but the surface properties still depend on the existence or absence of an atmosphere of normal matter to reprocess the pulsar radiation. The strange white dwarfs of Glendenning et al. (1995) would be difficult to distinguish from conventional carbon/helium ones.

The exotic nugget model predicts that no (carbon or helium) lines should ever be observed associated with the companion, in contrast to the expectations for a normal white dwarf or exotic analogue counterparts (Alford et al. 2011; Glendenning et al. 1995), which should show line features at some level of sensitivity. In addition, the lack of detection of evaporation signatures would naturally be accommodated, since no evidence of circumstellar material is found (Bailes et al. 2011). Finally, and because of angular momentum considerations of an ejected nugget, we expect the orbit **L** to be aligned with the spin of the pulsar. These are quite straightforward, unique predictions that need to be checked in future studies addressing the nature of this system.

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