

White dwarfs that crossed the Chandrasekhar limit: can modified Einstein's theory explain them?

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'A dying candle burns bright', so goes a saying. Similarly, supernova is a cataclysmic explosion that marks the death of a star.

A star is born in a flurry of dust cloud. In the beginning, it steadily accumulates matter and gathers more due to gravity. At a certain point, nuclear reaction is sparked at its core balancing the gravitational collapse and thus a star gets established. Once the star runs out of nuclear fuel, due to the crushing gravity, it violently explodes forming an outer shell and an inner core. This celestial firework is termed supernova. However, if the star is small, up to eight times the mass of the Sun, it undergoes a less violent and gradual dissipation dubbed as a planetary nebula. While the outer shell dissipates, the remnant ends up in diverse consequences which are determined by the mass that the star has accumulated. Ironically, more the mass a star accumulates, the brighter it will burn and sooner it will perish. As Lao Tzu, quips 'A flame that burns twice as bright, burns half as long'. Broadly, small stars end up as faintly visible white dwarfs, while large and

very large stars end up as neutron stars and black holes respectively (Figure 1). Thus, our Sun is destined to eject out a planetary nebula and end up as a white dwarf.

Chandrasekhar estimated that, as long as the end stage of a less massive star resulting from a planetary nebula is less than 1.44 times the mass of the Sun [M_{\odot}], it survives as a faintly visible white dwarf (Box 1). However, consider a situation where a white dwarf (with mass less than $1.44 M_{\odot}$) begins to accumulate mass from a neighbouring star or interstellar dust. Gradually, as it accumulates mass and approaches the Chandrasekhar limit of $1.44 M_{\odot}$, it catastrophically explodes again into a supernova (Figure 2). These supernovae are different from the usual ones, as they are formed following the dormant phase of stars – white dwarf and are called type Ia supernova (SNe Ia). They leave no residue as in the case of the aforementioned supernovae. Naturally, all type Ia supernovae have identical progenitor mass of $1.44 M_{\odot}$.

The luminosity of a celestial source is known to be a function of its mass;

higher the mass, greater the luminosity¹. Since the mass of the progenitors of any SNe Ia is $1.44 M_{\odot}$, the luminosity peak and spectra of all type Ia supernovae must be identical (Figure 3), but for the distance they are located from us. Therefore, cosmologists use these SNe Ia as standard candles to measure the distance to galaxies: SNe Ia located far away from us will appear fainter than those located closer to. Surprisingly, during 2003, a SNe Ia located in a galaxy 4 billion light years away, was observed to have a luminosity peak that exceeded the expected limit and additionally spewed matter at a lower velocity than expected. Clearly, the Chandrasekhar limit was crossed.

The observed luminosity peak corresponded to a progenitor white dwarf mass of $2.85 M_{\odot}$ (ref. 2) and was aptly nicknamed 'champagne supernova' based on a song by the band Oasis³. About a dozen such over-luminous 'champagne supernovae' have since been reported⁴, raising questions on the Chandrasekhar mass limit. To add to the surprise, there have been a few highly faint SNe Ia as well, whose corresponding masses are so low that according to the current understanding of physics, they could not have led to a supernova explosion. However, the under-luminous supernovae, though have been a matter of discussion since the 90s, were not as much of a surprise, as they were still below the Chandrasekhar limit. It is the over-luminous supernovae, otherwise forbidden, that have surprised physicists. Should we modify

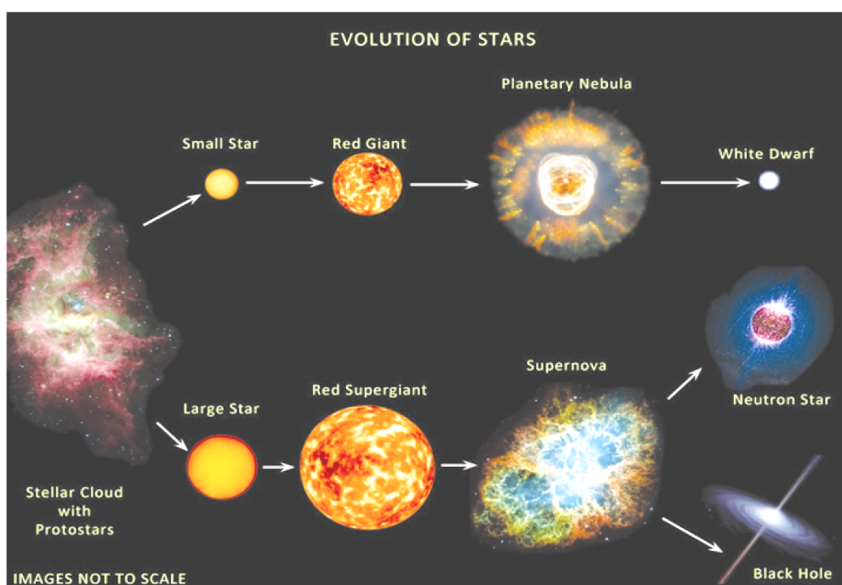


Figure 1. The evolution of small and large stars. Small stars, up to 8 times the mass of Sun, grow to be red giants and eventually shed their outer layer by forming a planetary nebula and form a white dwarf. Large and very large stars grow as super red giants, resulting in a supernova and end up as neutron star and black hole respectively. (Image credit: <http://essayweb.net/astronomy/blackhole.shtml>)

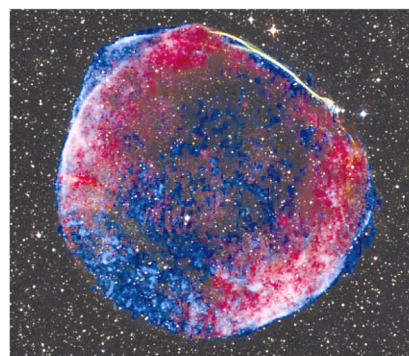


Figure 2. False colour image of a type Ia supernova. (Image credit: NASA, ESA, Zolt Levay (STScI))

our understanding of physics of the white dwarfs? Are the standard candles not 'standard' anymore?

A few hypotheses have been forwarded to account for the occurrence of over-luminous supernovae. Chandrasekhar, while deriving his famous mass limit, had assumed the white dwarf to be non-rotating and non-magnetized. However, it has been shown that a rapidly rotating white dwarf can exceed mass

limit⁵, but even this is not adequate to explain significantly super-Chandrasekhar supernovae progenitors⁶. Recently, Banibrata Mukhopadhyay and his team⁷ from the Indian Institute of Science, Bengaluru have proved that by considering a strongly magnetized white dwarf, the mass limit can reach $2.58 M_{\odot}$.

While these hypotheses can explain the over-luminous supernovae, they fail to include and explain under-luminous

supernovae. Consequently, a whole new set of ideas is needed to explain their existence, perhaps a generic hypothesis that can explain the occurrence of both. Das and Mukhopadhyay⁶, have precisely done this and have shown how modified Einstein's gravity theory can collectively explain the seemingly disconnected classes of supernova under a single description.

Einstein's theory of gravity establishes that space-time is curved around a massive object and it is scale-independent. Broadly speaking, irrespective of where we stand from the gravitating object, the force with which we are pulled is always equal to the inverse of the distance squared. But, the modified gravity theory, specifically Satarobinsky's model⁸ used by Mukhopadhyay and his group, deviates slightly from the current understanding. In this model, space-time around the gravitating object is curved *more* than what Einstein had predicted and the gravitational force term effectively has two components, namely the *inverse fourth* in addition to the inverse square of the distance. So, at close quarters to the gravitating object, the inverse fourth power of distance dominates, whereas farther away from the object the inverse square law operates according to Einstein's theory. This modification, in essence, can account for both the over-luminous and under-luminous supernovae and it is achieved by introducing a small perturbation by a scale factor α .

By varying the value of α , when the product of α and white dwarf density is conserved ($\rho\alpha = \text{constant}$), various mass limits are obtained. Values of positive α give under-luminous supernovae and negative values generate over-luminous supernovae (Figure 4). Thus, a single explanation can account for both over-luminous and under-luminous supernovae.

Since the work of Mukhopadhyay and his group is motivated by observations, this approach, which is perturbative, is applicable only for a range of α which successfully explains the observed supernovae and breaks down for values beyond this range where the technique becomes invalid. Mukhopadhyay clarifies, 'If an over-luminous type Ia supernova corresponding to say $5 M_{\odot}$ is discovered, we may not be able to use the same theory to explain it. Simply because the α value required to explain this, may be beyond the range allowed in

Box 1. White dwarf and the Chandrasekhar limit⁴.

In 1844, mathematician and astronomer Friedrich Wilhelm Bessel observed a strange wobbling orbit of Sirius¹⁰ and predicted that this was due to an invisible companion, circling along with it around their common centre of mass. Based on these observations, he calculated the period to be around 50 years and mass almost as much as the Sun ($0.98 M_{\odot}$). This invisible companion was named Sirius B and it remained invisible for the next two decades. In January 1862, Alvan G. Clark used the largest telescope available then and observed Sirius B for the first time and recorded its magnitude. It was found to be 400 times dimmer than the Sun and was too faint for a star as massive as the Sun. Two hypotheses were propounded to explain this low brightness: (1) low surface temperature – it is a cool star, and (2) low diameter – it is a small star. Obviously, it was essential to measure the temperature and/or diameter of the star to test these hypotheses.

In 1915, American astronomer Walter S. Adams recorded the spectrum of Sirius B and estimated its surface temperature to be around 10^7 K. Clearly, the star was faint not because of its coolness but because it was small – a star with the mass of the Sun but shrunk to the size of the earth. Quite naturally, the star must be exceptionally dense. In fact, its density is about a 100,000 times that of water, while that of Sun's core is just about 100 times. As Venkataraman¹¹ puts it, a tea cup full of white dwarf material is enough to balance 2000 elephants. Around the same time Ejnar Hertzsprung discovered another star with similar features – Omicron-2 Eridani. Soon several stars of this kind were discovered. Thus this problem was not only limited to Sirius B, but a new type of very high density stars were being discovered. These were aptly termed as white dwarfs because of their high temperature and tiny stature.

At that point in time, it was believed that nothing could have such high density. Hence, these white dwarfs posed a puzzle to the then physicists. Initially, the problem on very high density was resolved by Eddington¹², who showed that ionized matter may be dense, as the electrons indicating the limits or confinements of atoms do not exist. Once this was resolved, the problem of what balances gravity at this density was to be answered. Eventually after prolonged research on the topic, Chandrasekhar found a way to tackle this based on the works of Fowler, Milne, Stoner and Anderson. Fowler¹³ initially showed that even at absolute zero, electrons confined to a finite volume exert a finite pressure. It was later shown that this degeneracy pressure is responsible for the stability of white dwarfs. But in all these calculations Fowler and others assumed non-relativistic degeneracy pressure and it was Chandrasekhar who realized the need to apply relativity at such high densities and the mass limit automatically emerged. He is supposed to have cogitated about this on his famous ship voyage from India to England, and this work fetched him and Fowler the Nobel Prize in 1983. However, many still claim that Stoner and Anderson derived this mass limit even before Chandrasekhar¹⁴. The currently accepted mass limit is $1.39 M_{\odot}$ (ref. 15).

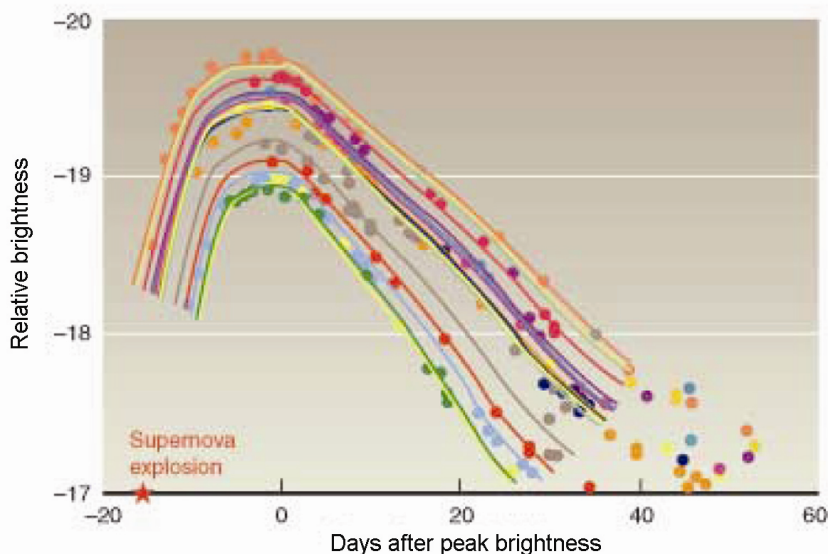


Figure 3. Type Ia supernova light identical light curves. (Image credit: Nordin, J. et al., 2010; <http://arxiv.org/abs/1011.6227v1>)

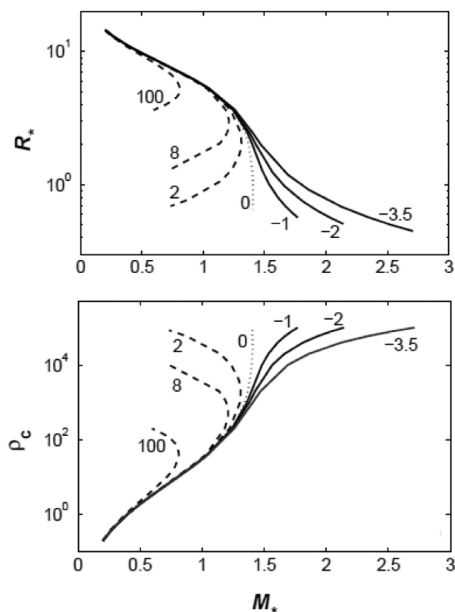


Figure 4. Different values of α giving rise to different mass limits⁶.

this theory. However, other modified gravity theories/models might work.’ Arapoğlu *et al.*⁹ have carried out such calculations for a neutron star and a similar range has been arrived at. In other words, there is more than one theory to explain over-luminous SNe Ia – the magnetized white dwarf and modified gravity.

When questioned which of the two might be right, Mukhopadhyay said ‘Both hypotheses are like my babies, I cannot pick between the two! However, from an astrophysicist’s perspective I

would think the magnetized white dwarf is likely to be the one. But they only explain the over-luminous. Therefore, in terms of aesthetics and an all-inclusive theory, I am personally hopeful the current modified gravity hypothesis is right. But eventually, only observations can give the final call. If Zeeman splitting is observed in the spectra of over-luminous SNe Ia, it could be proof for a magnetized white dwarf. On the other hand, if all theories fail to explain the champagne supernovae, the modified gravity could

in fact be the inevitable option for explaining the observed phenomenon. I must mention that the present work is just an exploration to show that modified gravity can have significant effect on white dwarfs, which were so far thought to be the case for neutron stars. One should now explore more appropriate, globally realistic models to establish them’. In future, Mukhopadhyay wishes to deal with other modified gravity models on white dwarfs and is hopeful to eventually find the parameter α as a function of a physical measure, which could bring the white dwarfs, neutron stars and the different epochs of the universe under a single theory.

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