164. Sub-subgiants and (tiny) black holes

FIFTY YEARS AGO, Hawking (1971) published a much-cited paper which posited that there may be a large number of primordial black holes of very small mass, 10^{-8} kg upwards, formed in the first second or so following the Big Bang. Their existence would obviate the need (through processes he detailed) for the very special initial conditions required to explain the Universe's high degree of isotropy, and indeed the very existence of galaxies. These primordial black holes might, in the process, provide a solution to the dark matter problem.

He contended that a mass of 10^{14} kg of such objects could have accumulated at the centres of sun-like stars. If such a star later became a neutron star, there would be *... a steady accretion of matter by the central collapsed object, which could eventually swallow up the whole star in about ten million years.*

Hawking further proposed that the Sun itself may harbour such a primordial black hole at its core, whose accretion would supply part of the solar luminosity.

LET ME PLACE that remarkable idea to one side (I will return to it later), and introduce the seemingly unrelated topics of subgiants, and blue and red stragglers.

First, subgiants. Their discovery, their role in the early understanding of stellar evolution, their importance in the age dating of the Galactic disk, and the insights provided by Hipparcos, were reviewed by Sandage et al. (2003). The term was first used by Strömberg (1930): their discovery did not fit the picture of stellar evolution developed by Russell in the years 1914–30, in which stars were believed to be born as giants near $M_V = 0$, after which (it was surmised) they contracted, becoming hotter, until reaching the main sequence.

A deep M67 colour–magnitude diagram provided the key to the now-accepted explanation, and post-1960 terminology (Johnson & Sandage, 1955): that the giant-branch is the locus of stars on the 'first ascent' of the post-main-sequence in a H shell burning phase, after core-H exhaustion. The He flash, at the top of the first-ascent branch, is followed by the descent to the core He-burning phase, populated by the 'clump' giants.

SUBGIANTS capture the transition from the main sequence to the red giant branch, and occupy the roughly 'horizontal' part of of the evolutionary track between the main sequence and giant stages: the start of H-shell burning is accompanied by an increase in radius, and a movement away from the main sequence. They lie just above the main sequence and to the left of the Hertzsprung gap for the more massive stars, and on the slow rise up the lower giant branch for low-mass stars. Their rapid evolution means that they are rare in the solar neighbourhood: Hipparcos observed only 12, including the nearest and brightest, β Hyi.

Blue stragglers, meanwhile, were first identified by Sandage (1953). Most easily identified in stellar clusters (by exploiting their common ages), they are more luminous, and have a higher effective temperature (therefore bluer) than the cluster's main sequence turnoff point. Inconsistent with standard stellar evolutionary theory – since they should have consumed their nuclear fuel, and evolved to become white dwarfs long ago – the consensus is that they are either binary stars in the process of merging (or that have recently merged), or a result of mass-transfer in a binary system (Mapelli et al., 2006). 'Yellow stragglers' are believed to be in an even more advanced evolution stage. A workshop in 2012 was devoted to their collective understanding (Boffin et al., 2015).

BLUE STRAGGLERS are not the central topic of this essay, but let me note that Gaia is contributing to their understanding, mainly by providing the much improved location of previously suspected candidates in the colour–magnitude diagram, and rejecting others.

The catalogue of Ahumada & Lapasset (2007) listed 1887 candidates in 427 open clusters. Using Gaia DR2, Rain et al. (2021) were only able to confirm a small subset, amounting to 897 blue stragglers, and 77 yellow stragglers, in 408 open clusters. Around the same time, also from DR2, Jadhav & Subramaniam (2021) found 868 blue stragglers in 228 clusters. And they established that their numbers *increase* with cluster age and mass. Using Gaia DR3, Li et al. (2023) found a further 138.

THE NAMING became more confusing when Belloni et al. (1998) discovered a new class of star, in M67, that they termed 'sub-subgiants'. Defined empirically in the optical colour–magnitude diagram, they fall redward of the normal main sequence, while being *fainter* than the subgiant and giant branches (see also Mathieu et al., 2003). Similar stars in the globular cluster 47 Tuc were termed 'red stragglers' (Albrow et al., 2001). Other examples have since been discovered in both open and globular clusters, as well as in the field.

Geller et al. (2017) attempted to clarify the confusing nomenclature, and (with reference to their Figure 1) recommended use of the term 'sub-subgiant' to refer to stars that are redder than the normal main-sequence and *fainter* than normal subgiants, and the term 'red straggler' to stars similarly redder than the normal red giants but *brighter* than normal subgiants. The latter were originally postulated to be either former blue stragglers evolving toward the giant branch, or binary star systems, or 'something more exotic' (Clark et al., 2004).

Based on a literature search, and their location in the colour–magnitude diagram, Geller et al. (2017) identified 65 sub-subgiants and red stragglers in 16 open and globular clusters. They found that 58% are X-ray sources (with properties similar to RS CVn active binaries), and at least 65% are variables, 21 of which are radial-velocity binaries. Taken together, they suggested that binarity is important for sub-subgiant formation. They nonetheless emphasised that, unexplained by standard theories of single-star evolution, their origin remained a mystery.

THREE EXPLANATIONS for the existence of these sub-subgiants were evaluated by means of (MESA) evolutionary models by Leiner et al. (2017): binary mass transfer, envelope stripping, and magnetic activity. In the latter scenario, sub-subgiants result from the rapid rotation in subgiants or giants due to tidal synchronisation in a close binary. The strong magnetic fields inhibit convection, which in turn produces large starspots, inflated stellar radii, and lower mean surface temperatures and luminosities. Of the three mechanisms, the magnetic-field mechanism was predicted to create the largest numbers of sub-subgiants in open clusters.

Parallaxes and photometry from Gaia EDR3 were later used by Leiner et al. (2022) to position known RS CVn (active giant) binaries in the colour–magnitude diagram. They classified stars that fall below a 14 Gyr, metal-rich isochrone as candidate field sub-subgiants.

Out of a sample of 1723 RS CVn, they found 448 sub-subgiant candidates from Gaia, a factor seven more than the 65 previously known. They concluded that the ubiquity of sub-subgiants amongst this population indicates that they are a normal evolutionary phase for RS CVn-type systems, rather than rare by-products of dynamical encounters found only in dense star clusters.

ALTHOUGH THE EXISTENCE of sub-subgiant stars is perhaps, at last, explicable by the normal evolution of RS CVn-type systems, and not least thanks to the high quality astrometry and photometry from Gaia, a more exotic origin, for at least some, has been suggested by Bellinger et al. (2023). And this links to the possible existence of primordial black holes that I mentioned at the start, and in particular to the formation of stellar-mass black holes if they grow through stellar capture.

The central idea is as follows: the Milky Way is expected to contain $\sim 10^8$ black holes from normal stellar evolution pathways, with an average separation of 21 pc (Sweeney et al., 2022). If dark matter is comprised of primordial black holes at the classical Hawking evaporation limit of $10^{-18} M_\odot$, the number increases to 10^{30} black holes with an average separation of ~1 au, raising the possibility of their capture by stars (Ilie et al., 2021).

Primordial black holes are considered to be an attractive solution to the dark matter problem because they require no modification to the standard model of particle physics. Possible approaches to their detection include gravitational wave signatures (e.g. Phukon et al., 2021) and gravitational microlensing (Carr et al., 2023).

Neither is the possibility of black holes existing inside normal stars a new idea, with evolutionary implications already considered by Clayton et al. (1975).

Incidentally, normal evolution models (i.e. without a central black hole) suggest that the Sun will evolve via a crystallising white dwarf into a black dwarf, and thereafter live on for a preposterously long time. In the absence of proton decay, pycnonuclear fusion, due to zero-point oscillations of nuclei around their equilibrium point, will slowly process their composition to ^{56}Fe, over a lifetime of 10^{1100} yr (Caplan, 2020).

FROM EVOLUTIONARY models of stars with a central black hole, Bellinger et al. (2023) found that the lightest black holes have little evolutionary influence, while the more massive progressively consume the star, and with various observable consequences. Models of the Sun born with a central black hole of mass $10^{-6} M_\odot$ are, they argue, compatible with current observations.

In this scenario, the Sun would first fade to half its current luminosity over a period of 100 Myr as the accretion starts to generate enough energy to quench nuclear reactions. It would then expand into a fully-convective star, where it would radiate for several Gyr with an enriched surface helium abundance, first as a sub-subgiant, and later as a red straggler, before becoming a sub-solar-mass black hole.

The unique internal structures of stars harbouring black holes may make it possible, they argue, for asteroseismology to confirm their existence.

Perhaps the Gaia-identified sub-subgiants, and red stragglers, offer a particularly interesting search sample.