254. Planet engulfment – and the Sun

Amongst a substantial literature on exoplanets is a significant body related to various aspects of planetary engulfment by their host star – a field greatly advanced by the Kepler mission (e.g. Lillo-Box et al., 2014).

For planets orbiting within ~0.2 au (considered to be delivered to such close orbits by gas disk migration, planet–planet scattering, or Lidov–Kozai resonance), tidal forces eventually lead to rotation axis alignment, synchronisation of their rotation and orbital periods, a reduction in orbit eccentricity and semi-major axis, and planetary tidal heating. The planet may spiral further inwards, and eventually merge with its host star (e.g. Jackson et al., 2009; Levrard et al., 2009; Ogilvie, 2014).

Some evidence for this also comes from the discovery that debris disks are reasonably common around white dwarfs (e.g. Koester et al., 2014). The related discovery of significant metal pollution in many white dwarf photospheres also demonstrates that a significant mass of collisional debris is being continuously accreted onto some white dwarfs, with spectral analyses providing diagnostics of the chemical composition of the debris (e.g. Zuckerman, 2015; Williams et al., 2024).

Broadly, planets in initial orbits within the final extent of the red giant envelope will be engulfed and migrate inwards (e.g. MacLeod et al., 2018; O'Connor et al., 2023). Incidentally, the first such 'polluted' white dwarf discovered from Gaia was reported by Melis et al. (2018).

Whether planetary companions to white dwarfs exist, having survived the red-giant and asymptotic-giant branch phases, depends on initial orbit separations, stellar mass-loss rate, tidal forces, and interactions with the ejected material (e.g. Gould & Kilic, 2008). Indeed, Sanderson et al. (2022) have predicted that Gaia will detect 8 ± 2 planets around white dwarfs from the astrometric motion of the system's photocentre.

As for Earth's future beyond the Sun's main sequence lifetime, various studies have been made of the consequences for planetary orbits and engulfment, tidal interactions, and gravitational escape as a result of mass loss (e.g. Schröder & Smith, 2008; Veras & Wyatt, 2012).

The decreasing mass of a star's outer convective zone as a function of stellar mass implies that contamination of the atmosphere by accreted planetary material should preferentially affect hotter stars. Early studies failed to identify such a trend (Pinsonneault et al., 2001), although observations and theoretical studies continue (e.g. Dotter et al., 2017; Behmard et al., 2023a; 2023b; Soares et al., 2025; Soliman & Hopkins, 2025).

Adding to the challenge of unambiguously identifying evidence of past planetary engulfment is the fact that planetary formation itself removes refractory material from the protostellar disk, resulting in correlations between elemental abundance differences and the dust condensation temperature (e.g. Lodders, 2003; Meléndez et al., 2009; Chambers, 2010; Booth & Owen, 2020; Hühn & Bitsch, 2023; Ghezzi et al., 2026).

Binary systems offer a particularly important testing ground, for those with or without known planetary companions. In either case, if one component is richer in refractory elements (e.g., Fe, Si, Mg) than the other, this might point to a past planetary engulfment.

Early studies indeed found some cases of large abundance differences ($\Delta[\mathrm{Fe/H}] > 0.01$ dex), although these were possibly resulting from chemical inhomogeneities in the protostellar gas clouds (e.g. Gratton et al., 2001; Desidera et al., 2004; 2006; Ramírez et al., 2015; Teske et al., 2016; Saffe et al., 2017; Oh et al., 2018; Ryabchikova et al., 2022).

The challenge is nicely formulated by Spina et al. (2021): *'It is still unclear whether the abundance variations are the result of chemical inhomogeneities in the protostellar gas clouds or instead if they are due to planet engulfment events occurred after the stellar formation. While the former scenario would undermine the belief that the chemical makeup of a star provides the fossil information of the environment where it formed, a key assumption made by several studies of our Galaxy, the second scenario would shed light on the possible evolutionary paths of planetary systems.'*

GAIA IS MAKING several fundamental contributions. Crucially, the combination of astrometry, photometry, and RVS spectra from Gaia EDR3 has provided a well-defined sample of more than one million binaries (El-Badry et al., 2021, cf. essay 134). Amongst these, Gaia astrometry permits the robust identification of *boun*d systems, even those with very large separations.

Further, and consistent with the idea that bound binaries originate in a molecular cloud with a reasonably homogenous chemical composition, Gaia results suggest that the chemical abundances of comoving pairs, even with large separations, are *generally* consistent to $\sim$0.1 dex (e.g. Kamdar et al., 2019; Nelson et al., 2021).

Several Gaia-based studies are now focusing on the abundance differences in wide separation binaries, originally using DR2 (Nagar et al., 2020), and subsequently EDR3 (e.g. Spina et al., 2021; Yana Galarza et al., 2021; Yong et al., 2023; Lim et al., 2024; Teske, 2024), and most recently DR3 (Yana Galarza et al., 2024).

Amongst these, Nagar et al. (2020) identified 6 chemically anomalous systems out of 14 studied, including HIP 34407/HIP 34426, with a mean Δ[Fe/H] = 0.19 dex. Their results also show a trend between differential abundances and condensation temperature, suggesting that the anomaly is indeed due to a past engulfment.

For the wide (17 kau) binary HIP 71726/HIP 71737, Yana Galarza et al. (2021) argued that both the enhancement in refractory elements (Δ[Fe/H] $= 0.11 \pm 0.01$ dex) in HIP 71726, and its high Li content, could be explained by planet engulfment, specifically by the ingestion of $9.8 \pm 1.8 M_\oplus$ of rocky material.

TWO STUDIES HAVE worked with larger samples, both using Gaia EDR3, but with rather different findings. Spina et al. (2021) selected 107 binaries comprising solar-type stars ($T_{\rm eff} < 6500$ K) with similar $T_{\rm eff}$ and $\log g$ (within 600 K and 0.6 dex respectively). For 33 systems, Fe abundances are different at $> 2\sigma$, and correlated with $T_{\rm eff}$. Again, such a dependency is predicted for planet engulfment, where stars with lower $T_{\rm eff}$ have deeper convection zones capable of ingesting planetary debris without greatly affecting their overall composition (Pinsonneault et al., 2001). They concluded that planet engulfment occurs in 20–35% of Sun-like stars.

Liu et al. (2024) studied 91 conatal binaries with separations $< 10^6$ au (and 34 wider systems considered as a control sample). From high-precision spectroscopic abundances, they attributed (at least) 7 instances to planetary ingestion, implying an occurrence rate of 8%.

They argued that their results are consistent with previous studies of solar twins by Ramírez et al. (2009). They attribute their lower engulfment rates compared with those of Spina et al. (2021), to their more homogeneous sample, and their use of a larger set of diagnostic elements, rather than mainly C and Fe.

THERE ARE SOME interesting implications for understanding our own solar system. This, in turn, extends to prospects for optimising the search for solar 'twins' (essay 17) amongst other Sun-like stars – perhaps those stars more likely to host Earth-like planets.

Specifically, the Sun has an unusual (and still unexplained) chemical composition compared to other Sun-like stars, with less refractory elements (e.g. Meléndez et al., 2009; Ramírez et al., 2009; Bedell et al., 2018; Asplund et al., 2021), and lithium (Carlos et al., 2019).

All these authors have suggested that this is a signature of the planet formation that occurred around the Sun, but not in the majority of solar twins. It may be linked to the distinctively ordered architecture of our solar system, which has preserved its planets on nearly circular orbits with very limited migration, contrasting with many known exoplanetary systems which may have had a much more dynamically violent past.

IN ADVANCING our understanding of the Sun's abundances in comparison with other solar twins, and their role in planet formation, Gaia is again making some significant contributions. This is in parallel with the creation of the latest catalogue of solar twins from Gaia (Taniguchi et al., 2026; Tsujimoto et al., 2026).

Specifically, most Sun-like stars do not yet have known abundances of refractory elements. Rampalli et al. (2024) addressed this by training a model on a reference set of 34 Gaia RVS stars ($R = 11\,200$) with abundances from high-resolution spectroscopy ($R > 30\,000 - 110\,000$). The model was then applied to a large sample of Gaia RVS solar analogues, yielding abundances (of C, N, O, Na, Mn, Cr, Si, Fe, Ni, Mg, V, Ca, Ti, Al, and Y) for 17 412 stars (50 of which are known planet hosts), with an average upper limit precision of 0.04–0.1 dex.

They found that the Sun remains refractory depleted compared to other Sun-like stars, regardless of any planets that they may host, a finding inconsistent with planets locking up or sequestering refractory elements.

TWO FURTHER Gaia DR3-based investigations have developed these ideas. Carlos et al. (2025) suggest that the Sun's peculiar composition is primarily related to Galactic chemical evolution, rather than the presence of giant planets.

Rampalli et al. (2025) showed that the trends of refractory elements versus condensation temperature arise because elements with higher condensation temperature have higher contributions from core-collapse supernovae. Refractory element depletion then primarily reflects nucleosynthetic enrichment, shaped by Galactic chemical evolution and ISM inhomogeneities.

Within this framework, the Sun then appears chemically unremarkable, lying within 0.5σ of the expected abundance distribution of solar analogues.