
120. Solar analogues – and our Sun

A ‘SOLAR ANALOGUE’ is loosely defined as a star that looks (or looked in the past, or will look in the future) ‘very similar’ to the Sun. Amongst objectives in searching for them is that they can provide a perspective of our Sun at some other point in its evolution.

In essay #17, I considered the related class of ‘solar siblings’, but also mentioned the term ‘solar twins’. The latter are taken to be a stricter (but still imprecisely) subset of solar analogues, viz. stars essentially *identical* to the Sun in all key astrophysical parameters: mass, age, luminosity, chemical composition, temperature, surface gravity, magnetic field, and so on.

Regardless of their origin, or location, solar *twins* may be those stars most likely to host planetary systems similar to our own, and therefore best-suited to host life based on carbon chemistry and water oceans.

Solar siblings, in contrast, are stars which are hypothesised to have formed at the same epoch as our Sun, and from the same gas cloud. While they would not need to be Sun-like in terms of properties such as effective temperature, mass, or luminosity, they would implicitly need to have identical ages, original chemical compositions, and share consistent Galactic kinematics.

As I described in essay #17, in their search for solar siblings, and exploiting the improved kinematical information in Gaia DR2, Webb et al. (2018) identified their top candidate, Solar Sibling 1, at a distance of 360 ± 80 pc.

To my knowledge, no further *sibling* candidates have been reported with Gaia DR3, and none of the pre-Gaia candidates, such as HD 186302 or HD 162826, have been further substantiated using the Gaia data.

HERE I LOOK at Gaia searches for solar *analogues*. I will explain in more detail why these searches are of interest, and draw attention to the (surprising) fact that the Gaia studies have enabled a significant improvement in our knowledge of the colour of... our Sun!

Much of my detail is from the more wide-ranging study describing ‘A Golden Sample of Astrophysical Parameters’, from Gaia DR3, by Creevey et al. (2022), who have produced a list of 5 863 solar analogues!

LET ME AGAIN recall that there is no strict definition of what constitutes a solar analogue. Searches aim to constrain the properties that can be determined by photometry or spectroscopy (T_{eff} , $\log g$, and metallicity $[M/H]$) to within the measurement uncertainties. While accuracies of 10 K in T_{eff} , 0.03 in $\log g$ and 0.01 in $[M/H]$ are achievable, 50 K, 0.15 and 0.05 are more typical.

WHY ARE searches and studies of solar *analogues* of scientific interest? A first answer is that studying the ways in which the chemistry of the Sun differs in detail from stars that are otherwise broadly similar may point to whether our Sun is typical, or otherwise, amongst stars hosting Earth-like planets.

As an example, when selected to be well matched in iron abundance, $[Fe/H]$, the Sun is among the 10–15% of nearby solar analogues rich in volatile elements (Meléndez et al., 2009). The observed trend of element abundance versus condensation temperature may be related to selective accretion of gas compared with dust due to the presence of planets.

Solar analogues have also been used to identify abundance ratios which depend most sensitively on stellar age, and can thus serve as accurate spectroscopic ‘clocks’, with the $[Y/Mg]$ abundance ratio being particularly sensitive (e.g. da Silva et al., 2012; Nissen, 2015).

Solar analogues also assist in the mineralogical study of minor bodies of the solar system, where they can be used to subtract the solar spectrum from reflectance spectroscopy of asteroids with the aim of a more uniform classification (e.g. Lazzaro et al., 2004; Jasmim et al., 2013; Galluccio et al., 2022).

Other applications include setting the zero point of photometric calibrations (e.g. Holmberg et al., 2006; Casagrande et al., 2021); testing stellar interiors through asteroseismology (e.g. Chaplin et al., 2011; Bazot et al., 2018); chemical evolution of the Galactic disk (e.g. da Silva et al., 2012; Botelho et al., 2020); in the study of the neutron-capture elements (e.g. Meléndez et al., 2014; Yana Galarza et al., 2016); and the ‘odd–even’ effect in supernova nucleosynthesis (Yana Galarza et al., 2021).

GAIA SPECTROPHOTOMETRY enables a uniform and powerful search across millions of stars, with the accurate parallax distances providing further constraints on masses, radii, and luminosities.

Of large-scale searches, Yana Galarza et al. (2021) used constraints on absolute magnitude and colour, using photometry from Gaia DR2 and EDR3, to identify solar twins and solar analogues within 100 pc, in combination with high-resolution spectroscopy from the ground. Their photometric constraints, for example, included $M_G = 3.755 - 5.331$, $G_{BP} - G = 0.254 - 0.377$, $G - G_{RP} = 0.455 - 0.589$, and $G_{BP} - G_{RP} = 0.761 - 0.907$.

They reported 46 solar analogues and 9 solar twins.

IN A MORE extensive study of solar analogues based on Gaia DR3, Creevey et al. (2022) initially selected stars brighter than $G < 16$, to allow efficient follow-up with ground-based spectroscopy, and with parallaxes better than 5%, to reliably place them in the Hertzsprung–Russell diagram.

They then used the results of the Gaia DPAC (Data Processing and Analysis Consortium) GSP–Spec classification module, as applied to the mean RVS spectra (and detailed further in essay #89). The results of the FLAME module (Final Age and Mass Estimates) was used to restrict candidate masses to the interval $0.95 - 1.05M_\odot$, and radii to the interval $0.8 - 1.2R_\odot$.

They also verified that the candidates have $[\alpha/\text{Fe}]$ abundances that are statistically consistent with the solar value of zero, and made other tests on the estimated extinction values.

This resulted in 5863 GSP–Spec solar analogue candidates, of which 916 have RVS spectra published in Gaia DR3. Due to the selection on high parallax quality, the candidates tend to be nearby and thus scatter more or less uniformly over the whole sky.

They also created a (less stringent, and unpublished) candidate list from GSP–Phot, as applied to the G magnitude and BP/RP spectra, containing 234 779 solar analogue candidates, of which 7884 have RVS spectra.

That is the status of the first large-scale efforts at identifying solar analogue candidates from Gaia DR3. Given the scope of scientific applications that I have summarised above, it remains to be seen how others will use this remarkably substantial list.

ASERIES OF THREE papers, under the title of the Survey for Distant Solar Twins (SDST), aims to find and spectroscopically confirm distant (up to 4 kpc) solar twins and analogues. One of their objectives is to search for any variation of the fine structure constant α (quantifying the strength of electromagnetism) across the Galaxy. The method uses precise measurements of the wavelength separation of absorption-line pairs in stars Berke et al. (2023a). Solar analogues are particularly useful because they have many suitable pairs.

They used the following definitions of solar twins and analogues compared to solar values:

$$\text{solar twin} = \begin{cases} T_{\text{eff}\odot} \pm 100 \text{ K} \\ \log g_\odot \pm 0.2 \text{ dex} \\ [\text{Fe}/\text{H}]_\odot \pm 0.1 \text{ dex} \end{cases}$$

$$\text{solar analogue} = \begin{cases} T_{\text{eff}\odot} \pm 300 \text{ K} \\ \log g_\odot \pm 0.4 \text{ dex} \\ [\text{Fe}/\text{H}]_\odot \pm 0.3 \text{ dex} \end{cases}$$

Their use of Gaia EDR3 was more directed at verifying their spectroscopic estimates of T_{eff} , $\log g$ and $[\text{Fe}/\text{H}]$, with parallaxes defining their Galactic location. From an initial 877 candidates, they identified 206 out of 547 of the fainter stars ($G > 15.4$) with a high likelihood of being solar analogues, with 12 being good solar twin candidates. For the brighter ($G < 15.4$), they found 93 out of 330 likely solar analogues with 8 solar twin candidates.

They found no evidence for velocity separation differences for their sample of solar twins, limiting any local (< 50 pc) variations in α to 50 parts per billion (Berke et al., 2023b). But they also concluded that their diagnostic approach used for solar twins could also be extended to solar *analogues*, without significant additional systematic errors, allowing a much larger number of stars to be used as probes of any variation in α , and at much larger distances (Berke et al., 2023a).

ANOTHER interesting application of the present Gaia results on solar analogues is in the determination of the colours of the Sun or, in other words, our understanding of the solar flux as a function of wavelength.

The Sun's colours and absolute magnitude in various passbands are a key calibration point for a wide range of stellar, Galactic and extragalactic astronomy. But it is such a bright and well-resolved source that measurement in the standard astronomical passbands is not straightforward. One approach is to search for ‘Sun-like’ stars, which have very similar properties to the Sun and, from them, to infer the solar values (Holmberg et al., 2006; Casagrande & VandenBerg, 2006).

Creevey et al. (2022) started with their sample of 5863 solar analogue candidates noted previously, then selected 682 with reddening $A_0 < 0.001$ mag, to obtain mean colours and standard deviations for the Sun of

$$(G_{BP} - G_{RP})_\odot = (0.818 \pm 0.029) \text{ mag}$$

$$(G_{BP} - G)_\odot = (0.324 \pm 0.016) \text{ mag}$$

$$(G - G_{RP})_\odot = (0.494 \pm 0.020) \text{ mag}$$

$$(G - J)_\odot = (0.969 \pm 0.578) \text{ mag}$$

$$(G - H)_\odot = (1.292 \pm 0.401) \text{ mag}$$

$$(G - K_s)_\odot = (1.371 \pm 0.351) \text{ mag}$$

SOLAR ANALOGUES are set to become of more interest across several areas of astronomy. Gaia is discovering many thousands of new candidates, with a surprising range of potential applications lying ahead.