191. Extinction

A RECURRENT THEME in the Gaia literature is interstellar extinction. This is important in the determination of stellar parameters through spectral modelling (e.g. [M/H], $T_{\rm eff}$, and $\log g$), in the interpretation of some key evolutionary states, and in describing the distribution of gas and dust in the solar neighbourhood.

My goal here is to summarise *only* what has been measured with Gaia, and I will not touch on any scientific interpretation. Nor will I discuss the extra contribution of circumstellar dust around specific objects, nor atmospheric effects relevant for ground-based observers.

LIGHT is absorbed and scattered by gas and dust along the sight line from star to observer, and most stellar spectra are affected by at least some interstellar dust. The details and spatial variation of interstellar extinction depend on the properties of dust grains along a line-of-sight, and measurements also convey information about their composition and size distribution.

Interstellar extinction is rather a smooth function of wavelength, albeit with superimposed absorption features due to particular chemical species. These include the ultraviolet (217 nm) bump, diffuse interstellar bands (some seen in the Gaia RVS spectra; essays 92, 160), and others beyond Gaia's response in the infrared.

Extinction in a given direction can be inferred by comparing an observed spectrum with its closest atmosphere model. In the solar neighbourhood, extinction in the V-band averages some 0.7–1.0 mag kpc^{-1}, but it is much higher in specific regions, notably in the Galactic plane, and especially towards the Galactic centre.

Since blue light is more strongly attenuated than red, extinction also causes objects to appear redder as well as dimmer. This 'reddening' is often simply characterised by an object's *colour excess* in some specified photometric system, e.g. $E_{B-V} = (B-V)_{\rm obs} - (B-V)_0$.

The parameter $R \equiv A_V/E(B-V)$ characterises the ratio of total to selective extinction. Ranging between 2.2–5.8 for sight lines where ultraviolet extinction has been measured, a mean relationship $A_V = 3.1\,E(B-V)$ is frequently used (e.g. Cardelli et al., 1989; Fitzpatrick, 1999; Fitzpatrick & Massa, 2007).

THERE IS A HUGE literature on extinction, and historical advances have also followed from ultraviolet and (far-)infrared observations. Early studies were made by Trumpler (1930), van Rhijn (1949), Schatzman (1950), Münch (1952), Chandrasekhar & Münch (1952), Gottlieb & Upson (1969), Milne & Aller (1980), and Neckel & Klare (1980), Arenou et al. (1992) and many others.

For extragalactic astronomy, and as a foreground in interpreting the Cosmic Microwave Background, a two-dimensional map of *integrated* dust extinction and reddening is usually sufficient. The maps of Schlegel et al. (1998), based on IRAS 100 μm and COBE–DIRBE 100 μm and 240 μm data, are still some of the most widely used corrections (e.g. Malhan & Rix, 2024).

THE IMPROVED HIPPARCOS distances advanced the determination of spatial variations within the Galaxy. Vergely et al. (1998) used extinctions determined from Strömgren photometry and Hipparcos parallaxes for 11 837 stars with $r < 400$ pc, from which they derived an average opacity $A_V = 1.5$ mag kpc^{-1}, and a scale-height of 70 pc. Hipparcos distances to open clusters were also used to construct extinction maps in the Galactic plane, $|b| < 10°$ (Chen et al., 1998; Joshi, 2005).

To extend the mapping horizon pre-Gaia, star distances were generally estimated from stellar spectral energy distribution models.

Drimmel et al. (2003) presented a model based on the COBE–DIRBE dust maps. The dust distribution was mapped in greater detail using near-infrared colours from 2MASS (Marshall et al., 2006), and using optical and near-infrared colours from SDSS (Berry et al., 2012).

Probabilistic (Bayesian) models, inferring both the distribution of dust and the stellar types and distances, were derived from the INT Photometric Hα Survey of the Northern Galactic Plane (Sale et al., 2014), and from Pan-STARRS 1 and 2MASS photometry of 800 million stars over three-quarters of the sky, which extended the mapping to several kpc (Green et al., 2015; Green et al., 2018). Lallement et al. (2014) used 23 000 sight lines to trace the dust within 2.5 kpc, adopting a Gaussian weighting to enforce smoothness on small spatial scales.

Around the time of the Gaia launch, Lallement et al. (2014) noted that *'3D maps of the Galactic interstellar matter are a potential tool of wide use, but accurate and detailed maps are still lacking'*.

Gaia is changing this. Accurate parallaxes provide the means of quantifying the dependence of extinction on distance for millions of sight lines in the Galaxy. And in addition, reddening and extinction *for each star* can be estimated from the low-resolution BP/RP spectra, and from the RVS spectra. Because successive Gaia data releases supersede the previous, I will summarise the early results only briefly. The referenced papers generally also provide links to their derived extinction maps.

Using DR2, Andrae et al. (2018) derived G-band extinctions (A_G) and $E(B_\mathrm{P} - R_\mathrm{P})$, for 88 million sources, but based only on integrated photometry (G_BP, G_RP), and broad assumptions. Leike & Enßlin (2019) used a Gaussian process model using these extinctions to derive reddening maps within a few hundred pc.

Chen et al. (2019) used DR2 parallaxes, (G_BP, G_RP) photometry, and infrared photometry from 2MASS and WISE, to derive $E(G - K_\mathrm{S})$, $E(B_\mathrm{P} - R_\mathrm{P})$, and $E(H - K_\mathrm{S})$ for 56 million stars in the Galactic plane, with an angular resolution of 6 arcmin. The dust shows the disk warp, and complex structures associated with the Sagittarius, Local, and Perseus arms.

Lallement et al. (2019) used DR2 parallaxes with DR2 and 2MASS photometry to derive the dust distribution in a $6 \times 6 \times 0.8$ kpc^3 volume centred on the Sun. They discussed various features evident in the Carina–Sagittarius arm, the Local arm/Cygnus Rift, and the Perseus arm (including a wavy pattern in some regions), and the link between the dust concentrations and the locations of molecular clouds, H II regions, O stars, and masers.

Green et al. (2019) derived reddening maps from 799 million stars with $\delta > -30°$ and out to a few kpc, using DR2 parallaxes combined with Pan-STARRS1 and 2MASS photometry.

Anders et al. (2019) used DR2 parallaxes and photometry, along with Pan-STARRS1, 2MASS, and AllWISE photometry for 137 million stars with $G < 18$, yielding a median precision of 0.20 mag in A_V for $G \leq 14$. Amongst their extinction-corrected colour–magnitude diagrams, there is a clear manifestation of the Galactic bar in the stellar density distributions.

Sun et al. (2022) used Gaia DR2 photometry combined with LAMOST photometry to determine reddening maps for 2 million stars, comparing them favourably with the widely used maps of Schlegel et al. (1998).

With EDR3, several improved and updated maps, based on the same general methods, were constructed and made available (Anders et al., 2022; Lallement et al., 2022; Vergely et al., 2022).

Substantial improvements came with the availability of Gaia DR3, in part from the improved parallaxes, but also with the availability of the mean BP/RP (aka XP) spectra for 220 million stars (see essay 189). For their determination of atmospheric parameters using GSP–Phot to match the XP spectra, Andrae et al. (2023a) actually used the Fitzpatrick (1999) mean extinction law.

Kordopatis et al. (2023) used parallaxes, atmospheric parameters, 2MASS and Gaia EDR3 photometry to compute ages, masses, and reddenings for 5 million stars with RVS spectra. Another model using Gaia, 2MASS and ALLWISE was given by O'Callaghan et al. (2023).

Revised extinctions were also derived through improved reductions of the XP spectra (essay 189), viz. the 220 million stars of Zhang et al. (2023), the 175 million sample of Andrae et al. (2023b), and the 48 million sample of Hattori (2024). Using the XP spectra on a slightly different metallicity scale, based on empirically calibrated theoretical models, An et al. (2024) determined both reddening and metallicity for 80 million main-sequence stars, modelling foreground extinction out to approximately 3 kpc.

Amongst the latest, Gontcharov et al. (2023a) used Gaia, Pan-STARRS1, SkyMapper, 2MASS, and WISE photometry for 100 million stars to derive 3D extinction maps in V and G within 2 kpc (resolution 3.6–11.6 pc transverse and 50 pc radial; see their Fig. 10), a 3D differential extinction map, and a 2D map of total Galactic extinction for Galactic latitudes $|b| > 13°$, and with a precision in A_V of 0.06 mag. An analytical model, treating the 3D dust distribution as a superposition of three overlapping layers, is given by Gontcharov et al. (2023b).

The XP spectra also allow determination of extinction at their spectral resolution, $R \sim 20-100$. Zhang et al. (2023) constructed a 'universal extinction' versus wavelength curve, derived from the data without reference to any previous model, and with each wavelength interval modelled separately. The resulting smooth extinction curve (their Fig. 15) agrees reasonably well with the $A_V = 3.1\,E(B - V)$ model of Cardelli et al. (1989).

Let me recall that this essay has focused on extinction estimates based on the Gaia data, and does not cover other ongoing efforts, such as with JWST (e.g. Wang & Chen, 2024), and others (e.g. Yu et al., 2023).

Let me also mention that specific sky regions are often subject to specialised extinction studies, especially towards the Galactic bulge (e.g. Nataf et al., 2013; Nataf et al., 2016), and towards the SMC and LMC (e.g. Prevot et al., 1984; Fitzpatrick, 1986; Wang & Chen, 2023).

Even with Gaia DR3, several extinction maps and calibrations are now available. Absent some wider consensus, each user must make their own choice!