Lithium pollution of a white dwarf records the accretion of an extrasolar planetesimal

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Tidal disruption and subsequent accretion of planetesimals by white dwarfs can reveal the elemental abundances of rocky bodies in exoplanetary systems. Those abundances provide information on the composition of the nebula from which the systems formed, which is analogous to how meteorite abundances inform our understanding of the early Solar System. We report the detection of lithium, sodium, potassium, and calcium in the atmosphere of the white dwarf Gaia DR2 4353607450860305024, which we ascribe to the accretion of a planetesimal. Using model atmospheres, we determine abundance ratios of these elements, and, with the exception of lithium, they are consistent with meteoritic values in the Solar System. We compare the measured lithium abundance with measurements in old stars and with expectations from Big Bang nucleosynthesis.

White dwarfs are remnants of main-sequence stars that have exhausted their available nuclear fuel and have expelled their outer layers to leave a hot, planet-sized object, which cools over billions of years. Their high surface gravities cause stratification of elements by mass, so undisturbed white dwarf atmospheres should exhibit spectral lines of only the lightest element present, usually hydrogen or helium. However, many white dwarf spectra show evidence of atmospheric contamination by heavier elements (referred to as pollution), which in some cases is accompanied by an excess in infrared emission caused by a surrounding dust disk. These are attributed to the tidal disruption and accretion of extrasolar planetesimals \textsuperscript{(1–4)}.

Surveys indicate that up to half of hot white dwarfs show atmospheric pollution \textsuperscript{(2, 5, 6)} by elements that are expected to sink below the surface on time scales of approximately days to approximately millions of years \textsuperscript{(7)}, so planetesimal disruption and accretion must be a frequent event. In white dwarf atmospheres where the abundances of all major rock-forming elements have been measured, the extrasolar planetesimal compositions resemble those of the bulk Earth or other rocky Solar System bodies \textsuperscript{(8–10)}. Abundances have mostly been measured from white dwarfs with effective temperatures \textgtrsim 4500 K, as cooler (therefore older) white dwarfs are faint and difficult to study \textsuperscript{(9, 11, 12)}. A sample of 230 metal-polluted white dwarfs included only two with cooling ages \textgtrsim 7 billion years (Gyr), and most were younger than 4 to 5 Gyr \textsuperscript{(11)}. The Solar System is 4.5 Gyr old, so the compositions of exoplanets that formed at earlier times are unknown.

We observed the white dwarf (WD) Gaia DR2 4353607450860305024 (WD J1644-0449) as part of a survey of ultracool objects selected from the Gaia Data Release 2 (DR2) catalog \textsuperscript{(13, 14)}, chosen to have temperatures \textless 4500 K and total (main-sequence plus white dwarf cooling) ages \textgtrsim 7 Gyr. We expect elemental abundances of these systems to reflect Galactic chemical enrichment at their epoch of formation, as has been measured in the atmospheres of similarly old stars \textsuperscript{(15)}. WD J1644-0449 is not in previous white dwarf catalogs derived from Gaia data \textsuperscript{(16, 17)} because its color is redder than the usual selection criteria. We obtained optical spectra of WD J1644-0449 using the Goodman Spectrograph mounted on the 4.1-m Southern Astrophysical Research (SOAR) telescope \textsuperscript{(18)}. We examined archival infrared photometry \textsuperscript{(18)} and found no infrared excess indicative of a cool companion or dust disk.

Our spectra show (Fig. 1) that WD J1644-0449 is a white dwarf of spectral type DZ that exhibits several heavy element absorption features. The effective temperature is too low for the spectrum to show optical absorption lines of atomic H or He even if they dominate the atmosphere (as we expect). The dominant spectral feature is a broad and deep Na I D absorption line reminiscent of two previously known white dwarfs: WD J2356-209 and (Sloan Digital Sky Survey) SDSS J133001.13+643523.7 (hereafter SDSS J1330+6435) \textsuperscript{(19, 20)}. Broad Ca II H and K lines overlap a broad Ca I line, and a further broad dip is present at the wavelength of a molecular band of MgH. We also identified a K I line, and, in two different instrument modes, we detected an absorption feature centered at 6710 Å, which we identify as a Li I line with a rest wavelength of 6708 Å.

We examined published spectra of other white dwarfs known to have broad Na I D lines \textsuperscript{(19, 20)} and found that SDSS J1330+6435 also shows an absorption line at the location of the same Li I line. This line was visible in a prior publication but was not identified, perhaps because of the low signal-to-noise ratio of the spectrum \textsuperscript{(21)}. WD J2356-209 does not show \hfill

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Fig. 1. Spectrum of WD J1644-0449. Data (black) are overlaid with the best-fitting model (red line). The spectrum was constructed by combining two observations above and below 6800 Å \textsuperscript{(18)}. Gray bands show regions of telluric absorption from Earth’s atmosphere \textsuperscript{(31)}; we applied telluric corrections at wavelengths \textgtrsim 6800 Å. Labeled absorption lines include Ca II H and K (3934 and 3969 Å), Ca I (4226 Å), MgH band (5190 Å), Na I D (5893 Å), Li I (6708 Å), and K I (7665 and 7699 Å).
any evidence for Li absorption (19). We re-observed WD J2356–209 with the Goodman Spectrograph and again did not detect any Li or K lines (fig. S3), but we placed upper limits on their abundances that are tighter than previously available (12).

To determine atmospheric abundances, we calculated a grid of white dwarf atmosphere models by adding Li to previously published models (22). We also used models to evaluate the mass contained in the surface convection layer and the masses of accreted elements that are expected to be mixed in this convection zone. We used a theoretical mass-radius relation to estimate the stellar mass and radius consistently with all the data (18, 23). We estimated the temperature of WD J1644–0449 to be 3830 ± 230 K—very cool for a metal-polluted white dwarf.

The detection of Li allows us to investigate the Li abundance of extrasolar planetesimals and compare them with both the atmospheres of stars with similar ages (24) and the expectations of Li formation during Big Bang nucleosynthesis (BBN) (25). Li can be strongly depleted in stellar atmospheres, including in the Sun, because it is consumed by nuclear reactions at a lower temperature than H. However, Li is incorporated into meteorites and planetesimals because it is only moderately volatile—condensing at higher temperatures than either Na or K (26). Thus, measurements of Li-polluted white dwarfs may offer a record of ancient Li abundances. However, the measurements must be corrected for a possible bias introduced by the different rates at which elements sink in a white dwarf atmosphere.

Planetesimal accretion onto a white dwarf occurs in three phases. In the increasing phase, the star is actively accreting material from one or more planetesimals, and the atmospheric abundance ratios equal those of the accreted body. If accretion continues for several elemental sinking time scales, an equilibrium between accretion and diffusion is reached in which atmospheric abundance ratios approach a steady-state value that differs from that of the accreted body, but which can be corrected using the ratio of the sinking time scales (7, 10, 18). Once all accretion stops, the atmospheric abundances decrease exponentially at rates that are generally slower for lighter elements; abundance ratios then depend on both sinking times and the time elapsed since steady state accretion halted (7, 18). Figure 2 shows our measured abundance ratios and corrected ratios for the steady-state and decreasing phases calculated using the sinking times for Na, K, and Ca. For reference, we have also plotted abundance ratios for meteorites and a selection of Solar System bodies.

The K/Ca ratio in WD J1644–0449 remains nearly constant over accretion phases owing to the similar atomic masses and sinking times of these elements. Thus, the accreted body had a K/Ca ratio that falls in a region centered between the carbonaceous Ivuna-type (CI) and the carbonaceous Mighei–type (CM) chondrite meteorites shown in Fig. 2, regardless of the accretion phase. Chondrites are the most primitive meteorites in the Solar System, and CI chondrites are used to establish the initial composition of the Solar nebula on the basis of their abundance similarities to many elements in the Solar atmosphere (26). Unlike K, Na sinks more slowly than Ca, so the Na/Ca ratio would be enhanced in the atmosphere during a decreasing phase of accretion. Figure 2 shows that the inferred Na/Ca ratio would, in this case, be lower than that of CI or CM chondrites and would deviate from the sequence defined by Solar System bodies. This sequence arises because K and Na have nearly identical condensation temperatures and are both lithophile elements (i.e., they accumulate in the crust of differentiated bodies). On the basis of measurements of Na/Ca in the atmospheres of old stars in the solar neighborhood, which show mean deviations of <0.2 dex from Solar ratios (27), we expect that the Na/Ca abundance ratio in the gas from which WD J1644–0449 and its planetesimals formed is consistent with the Solar System value, within the uncertainties. Thus, we expect the planetesimal abundances for K/Ca and Na/Ca to fall along the same sequence as that defined by rocky bodies in the Solar System. This implies that the accretion is currently in a steady-state or early decreasing phase for WD J1644–0449. However, we also consider other accretion phases in our subsequent analysis.

The history of Li in the Galaxy is different from other elements and is more uncertain because of its destruction by nuclear burning in stars; in the solar atmosphere, Li is depleted by two orders of magnitude compared with the CI chondrites (26). BBN theory predicts that a substantial amount of Li formed in the first 5 min after the Big Bang. The
Fig. 3. Li/Ca evolution in the solar neighborhood. Logarithmic Li/Ca is shown as a function of age for a sample of typical stars from the Solar neighborhood (circles), and error bars in the lower right show typical 1σ uncertainties (15, 29). Because Li is consumed in stars, the highest values of log(Li/Ca) at each age represent the best proxy for interstellar gas values (32). The atmospheric values for the Li-polluted white dwarfs are shown with the same symbols as in Fig. 2 (18). White dwarf vertical error bars correspond to 1σ uncertainties; horizontal error bars correspond to the 68% confidence intervals. CI chondrites (blue square; 1σ vertical error bars are smaller than the symbol) represent the initial value for the Solar System, which is greater than the Sun’s atmosphere (blue circle; vertical error bars correspond to 1σ uncertainties) (26, 33). The age of the Universe is marked with the vertical dotted line (34).

Fig. 4. Spite diagram for the same sources as shown in previous figure. Li abundance A(Li) is shown as a function of iron abundance [Fe/H]. Predicted values for BBN and expected Galactic Li enrichment history are shown as the dashed line (25, 28). Symbols are the same as in Fig. 3. Sloped lines for each white dwarf represent abundances rescaled to A(Li) using log(Ca/Fe) relations for thick disk (solid lines) and thin disk (dotted lines) Galactic stellar populations, extending over the full range of those populations (18). The white dwarf symbol placement in [Fe/H] is representative and does not depict a preferred value (18).
interstellar medium (ISM) abundance remained close to the BBN value until the ISM Fe content was enriched by explosions of massive stars to a value of $-1.0 < [\text{Fe/H}] < -0.5$, where $[\text{Fe/H}]$ is the logarithm of the Fe-to-H ratio relative to the solar value (28). After that time, Li depletion by nuclear reactions in the main-sequence stars formed, which provides a sound basis for translating Li/Ca to Fe/Li. Figure 4 shows A(Li) for each accreted extrasolar planetesimal as lines extending from $-1.5 < [\text{Fe/H}] < 0.24$. We have included representative lines for the inferred A(Li) for WD J1644–0449 and SDSS J1330+6435 for two possible Galactic stellar populations (18). Each population line has a different transformation for Ca/Fe, but both have an upward slope reflecting the increase in our calculated A(Li) that results from increasing [Fe/H]. We also illustrate the differing A(Li) inferred for steady-state accretion or decreasing phase accretion.

The accreted bodies in Fig. 4 extend at low metallicities to A(Li) values compatible with BBN, but they do not extend below that prediction. They do not show evidence for the cosmological Li problem exhibited by the local stars. Thus, these Li-bearing extrasolar planetesimals represent an alternative to old stars for gaining insight into the primordial Li abundance, the earliest epochs of chemical enrichment in our Galaxy, and the properties of ancient exoplanets.

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calculations except the atmospheric and envelope modeling. S.B. performed the atmospheric modeling calculations and cowrote the manuscript. P.D. assisted with the atmospheric modeling calculations. R.J.H. obtained observations and assisted with the Li line identification. J.S.R. obtained observations. A.B. performed the envelope modeling and cowrote the supplement. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** The reduced Goodman spectra of WD J1644−0449 and WD J2356−209 are available in data S1 to S5. The SDSS J1330+6435 spectra are available from the SDSS archive (https://dr9.sdss.org/basicSpectra) with plate 0603, modified Julian date 52056, and fiber 0502. Our data reduction and analysis code is available on Zenodo (35). The atmosphere and envelope modeling software was written by a combination of authors (S.B. and P.D.) and nonauthors (G. Fontaine, P. Brassard, and P. Bergeron), so we cannot distribute the source code. An executable version with adjustable input parameters is available on Zenodo (36).

**SUPPLEMENTARY MATERIALS**

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Materials and Methods

Supplementary Text

Figs. S1 to S7

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Data S1 to S5

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