ExopLANETS-A: A virtual observatory database for host stars and planetary systems

The effect of XUV on planet atmospheres

M. Morales-Calderón¹, S.R.G. Joyce², J.P. Pye², D. Barrado¹, M. García Castro¹, C. Rodrigo¹, E. Solano¹, J.D. Nichols², P.O. Lagage³, A. Castro-González¹, R. A. García³, M. Guedel⁴, N. Huélamo³, Y. Metodieva⁴, and R. Waters⁵,⁶

¹ Centro de Astrobiología (CSIC-INTA), ESAC Campus, E-28692 Villanueva de la Cañada, Madrid, Spain e-mail: mariamc@cab.inta-csic.es
² School of Physics & Astronomy, University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom
³ Université Paris-Saclay, Université Paris ci, CEA, CNRS, AIM, 91191, Gif-sur-Yvette cedex, France
⁴ Department of Astrophysics, University of Vienna, Türkenschanzstr. 17, 1180 Vienna, Austria
⁵ Department of Astrophysics/IMAPP, Radboud University, PO Box 9010, 6500 GL Nijmegen, The Netherlands
⁶ SRON Netherlands Institute for Space Research, Niels Bohrweg 4, NL-2333 CA Leiden, the Netherlands

Received September 15, 1996; accepted March 16, 1997

ABSTRACT

Context. ExopLANETS-A is an EU Horizon-2020 project with the primary objective of establishing new knowledge on exoplanet atmospheres. Intimately related to this topic is the study of the host stars’ radiative properties in order to understand the environment in which exoplanets lie.

Aims. The aim of this work is to exploit archived data from space-based observatories and other public sources to produce uniform sets of stellar data that can establish new insight into the influence of the host star on the planetary atmosphere. We have compiled X-ray and UV luminosities, which affect the formation and the atmospheric properties of the planets, and stellar parameters, which impact the retrieval process of the planetary atmosphere’s properties and its errors.

Methods. Our sample is formed of all transiting-exoplanet systems observed by HST or Spitzer. It includes 205 exoplanets and their 114 host stars. We have built a catalogue with information extracted from public, online archives augmented by quantities derived by the Exoplanets-A work. In this catalogue we have implemented an online database that also includes X-ray and OHP spectra and TESS light curves. In addition, we have developed a tool, exoVOSA, that is able to fit the spectral energy distribution of exoplanets. Results. We give an example of using the database to study the effects of the host star high energy emission on the exoplanet atmosphere. The sample has a planet radius valley that is located at 1.8 Rₑ, in agreement with previous studies. Multiplanet systems in our sample were used to test the photoevaporation model and we find that out of 14 systems, only one significant case poses a contradiction to it (K2-3). In this case, the inner planet of the system is above the radius gap while the two exterior planets are both below it. This indicates that some factor not included in the photoevaporation model has increased the mass-loss timescale of the inner planet. In summary, the exoplanet and stellar resources compiled and generated by ExopLANETS-A form a sound basis for current JWST observations and for future work in the era of Ariel.

Key words. Stars: planetary systems – online catalogue – Extrasolar planet – stars: activity

1. Introduction

With the James Webb Space Telescope (JWST), it is possible to observe the composition and structure of exoplanet atmospheres using transit spectroscopy. In order to successfully model the exoplanet atmosphere, it is necessary to have sound knowledge of the host star, and particularly its radiation output. To this end, we have built a coherent and uniform database of the relevant properties of host stars from online archives, for example, the XMM-Newton XSA, Gaia DR2, SIMBAD and publications that are cited in the relevant sections. These exoplanet and host-star catalogues are accompanied by computer models to assess the importance of star–planet interactions, for example the ‘space weather’ effects of the star on its planetary system (Strugarek et al. 2022). The knowledge gained from this project is being published through peer-reviewed scientific journals, and modelling tools have been publicly released¹.

Seven institutes² in Europe combined their expertise in the field of exoplanetary research to develop the European Horizon-2020 ExoplANETS-A³ project (Lahuis et al. 2020) under the coordination of CEA Saclay. In the framework of the project, new

¹ Full publication list can be found at https://www.explore-exoplanets.eu/resource/project-publications/
² CEA Saclay, Paris, France; CAB-INTA, Madrid, Spain; MPIA, Heidelberg, Germany; University College London, U.K.; University of Leicester, U.K.; SRON, Utrecht, NL; Universitat Wien, Austria
³ Exoplanet Atmosphere New Emission Transmission Spectra Analysis; https://explore-exoplanets.eu/; The ExoplANETS-A project has received funding from the EU’s Horizon-2020 programme; Grant Agreement no. 776403, during the time period 2018 – 2021.

Article number, page 1 of 14
data calibration and spectral extraction tools, as well as novel
target retrieval tools, based on 3D models of exoplanet at-
mospheres, have been developed to exploit archival data from
space, and ground-based observatories, and have produced a ho-
mogeneous and reliable characterisation of the atmospheres of
transiting exoplanets. The project has six work packages (WPs);
the focus in this paper is on the WP 'Host star properties:
The active environment of exoplanets', and more specifically
the database containing the compiled catalogue, associated data
products, and the web-based user interface, that can be found at
http://svo2.cab.inta-csic.es/vocats/exostars/.

Properties of the exoplanet host stars are key factors to un-
derstanding the environment within which the exoplanet lies and
estimating the energy inputs to its atmosphere. This influence
comes via two different ways: the basic properties of the star
have an obvious effect on the planet and, in particular, X-ray
and UV luminosity affect the formation and the atmospheric
properties of the planets (Johnstone 2020; Becker et al. 2020;
Poppenhaeger, Ketzer, & Mallonn 2021). In addition to affecting
the physical condition of the planets, stellar parameters such
as its luminosity, effective temperature and radius have an im-
 pact on the retrieval process of the planetary-atmosphere prop-
erties and on its errors (Andersen & Korhonen 2015). There-
fore, a fully characterised host star is a mandatory first step for
ExoplANETS-A and for its main goal.

The paper is structured as follows. Section 2 describes the
compilation of the catalogue from the various data sources. Sec-
tion 3 describes the database and its associated software tools,
validation of the contents, and examples of statistics drawn from
the database. Section 4 discusses some uses of the database in
studying the influence of the host star on the exoplanet, while
Section 5 summarises the main conclusions. Appendix A gives
an example of accessing the database via the web-based user in-
terface.

2. Compilation & construction of the host stars
catalogue

2.1. Framework

The stellar properties catalogue comprises a compilation of in-
formation extracted from public, online astronomical archives
(databases and publications), augmented by quantities derived
from them by the ExoplANETS-A work. The overall work-
and data-flow are shown in schematic form in Fig.1. The
database and associated website\(^4\) were publicly released in De-

ce 2019, based on, and updated with information avail-
able from public, online sources up to ~October 2020, for the
ExoplANETS-A target list.

In addition, the database contains quantities derived from the
ExoplANETS-A project’s own (re)analysis of some of the public
data. The sample of exoplanets and host stars considered by the
project comprises all transiting-exoplanet systems observed by
Hubble (HST) or Spitzer space telescopes until June 2019. This
corresponds to 205 exoplanets, of which 121 have HST\(^\text{ data; the}
\)
associated number of stars is 114, with 77 having HST\(^\text{ data (Fig. 2).}
\)

2.2. Optical/IR data

Precise knowledge of stellar parameters is needed to fully char-
acterise the planet properties. For example, precise stellar radii
\(^4\) http://svo2.cab.inta-csic.es/vocats/exostars/.

Fig. 1. Work and data flow for the work package 'Host star properties: The active environment of exoplanets' in the ExoplANETS-A project.
2.3. X-ray and UV data

X-ray and UV radiation are produced by the host-star corona and chromosphere and are detected by several space-based observatories. For many targets, no significant X-ray detection is available. An X-ray upper limit can be estimated from the ROSAT all sky survey. These were gathered from the ESA Upper limit server (Saxton & Gimeno 2011) when available, yielding X-ray flux upper limits for 107 host stars. The Upper Limit server includes the ROSAT all sky survey (Voges et al. 1999) and the XMM-Newton (0.2-12 keV) 21 det, 19 UL observations of some new targets (Kepler-14 which is listed as an eclipsing binary in SIMBAD and only has a Gaia photometry value available for one of the stars).

The X-ray data are primarily from XMM-Newton pointed observations, along with several other Einstein and Exosat detections. The existing XMM observations were gathered from the XMM Science Archive, and observations of some new targets (Kepler-138, K2-3, HD3167) were obtained as part of observing program 084441 and 086206 (PI Joyce). Thirty targets have X-ray flux measurements available. The number of targets detected by each satellite (both in X-rays and UV) are listed in Table 1, along with other UV data. The number of detections in the 2-12 keV range that only cover the 2-12 keV range, should be treated with caution.

The Upper Limit server includes the Exosat low-energy survey (0.2-2keV), and these are included in the database where available. However, for the 4 targets mentioned, only 2-12 keV survey data were available.

The XMM-Newton X-ray flux values are recommended when available, due to the high sensitivity of the observatory and the relatively large and uniform set of available results. Detailed spectral fitting with 1- or 2-temperature APEC (Smith et al. 2001) optically thin plasma models was used to derive the X-ray flux from XMM-Newton spectra. For the values gathered from the Upper Limit server, a standard blackbody model with an appropriate temperature (0.3 keV) was used for the flux estimate because an optically thin plasma model is not implemented in the Upper Limit server. Fitting XMM spectra in xspec indicated that when using a blackbody model, the 0.3 keV temperature yielded a similar count-rate/fux ratio as the APEC model. We found that for the Exosat detections in the 2-12 keV range that a 0.3 keV blackbody resulted in an unrealistically high flux estimate, so the Exosat flux values in the catalogue are based on a 0.1 keV blackbody.

The UV data were gathered from the Galex all-sky surveys (Bianchi, Shiao, & Thilker 2017), which provide a flux and magnitude in the NUV (1770 - 2730 Å) range for 69 out of 114 stars. 23 stars also have an FUV (1350 - 1780 Å) flux available. The Galex data consist of broad-band photometry. Further UV data were gathered from the Swift (Neil Gehrels Swift Observatory, Gehrels et al. 2004) and XMM-Newton optical monitor (Mason et al. 2001). Another 7 targets were observed by the XMM-OM but were either saturated or not detected. Details where this occurred for each target are recorded in the database. The Swift UVOT and XMM-OM data consist of photometry in several bands depending on the filter(s) used for a particular observation.

The wavelength range relevant to each Swift or XMM-OM observation is given in the database. For example, the column named: 'column inst range Swift UVOT'. Galex data are recommended for studying the sample as a whole because data are available for most targets and provide a uniform analysis. Swift UVOT and XMM-OM UV data are useful as they are usually more recent than the Galex surveys that ended in 2012. Also, UV data are simultaneous with the X-ray data in the case of XMM-Newton.

---

Table 1. Observatories used to gather XUV data for stars in the catalogue.

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Wavelength ranges (Å or keV)</th>
<th>Number of detected targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROSAT</td>
<td>(0.2-2 keV)</td>
<td>30 unique targets</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>(0.2-12 keV)</td>
<td>7 det, 107 UL</td>
</tr>
<tr>
<td>Exosat</td>
<td>(2-12 keV)</td>
<td>21 det, 19 UL</td>
</tr>
<tr>
<td>Einstein</td>
<td>(0.2-2 keV)</td>
<td>6 det, 3 UL</td>
</tr>
<tr>
<td>Ultra-violet</td>
<td>(FUV, NUV)</td>
<td></td>
</tr>
<tr>
<td>Galex</td>
<td>1350-1780, 1770-2730</td>
<td>69</td>
</tr>
<tr>
<td>Swift-UVOT</td>
<td>Total</td>
<td>18</td>
</tr>
<tr>
<td>Swift-UVOT</td>
<td>u (3072-3857)</td>
<td></td>
</tr>
<tr>
<td>Swift-UVOT</td>
<td>uvw1 (2253-2946)</td>
<td></td>
</tr>
<tr>
<td>Swift-UVOT</td>
<td>uvm2 (1997-2495)</td>
<td></td>
</tr>
<tr>
<td>Swift-UVOT</td>
<td>uvw2 (1599-2256)</td>
<td></td>
</tr>
<tr>
<td>XMM-OM</td>
<td>Total</td>
<td>16</td>
</tr>
<tr>
<td>XMM-OM</td>
<td>U (3020-3860)</td>
<td></td>
</tr>
<tr>
<td>XMM-OM</td>
<td>UVW1 (2495-3325)</td>
<td></td>
</tr>
<tr>
<td>XMM-OM</td>
<td>UVM2 (2070-2550)</td>
<td></td>
</tr>
<tr>
<td>XMM-OM</td>
<td>UVW2 (1870-2370)</td>
<td></td>
</tr>
<tr>
<td>HST</td>
<td>Total</td>
<td>27</td>
</tr>
<tr>
<td>HST</td>
<td>Various COS 815 – 3200</td>
<td></td>
</tr>
<tr>
<td>HST</td>
<td>STIS 1150 – 3200 in UV</td>
<td></td>
</tr>
</tbody>
</table>

Notes. Column 2 lists the wavelength ranges covered by the various instruments and filters used for observations. Note that Swift-UVOT and XMM-OM filters do not cover exactly the same range, despite similar filter names. Column 3 lists the number of targets detected by each observatory which have flux measurements included in the catalogue. UL means targets have an upper limit value available rather than a detection.
Detailed UV spectra are available for 27 of the targets from HST pointed observations taken with the STIS and COS instruments. A subset of 13 have spectra taken with the COS G130M filter, that covers the 1100 - 1450 Å wavelength range. The analysis carried out for the database was limited to G130M observations to provide the most consistent analysis, but similar spectra are available for more host stars. For example, G140L spectra for WASP-13 and WASP-18 (e.g. Fossati et al. 2015, 2018). The G130M spectra have been analysed in more detail to provide broadband UV flux measurements as well as flux in specific lines that are useful diagnostics of the stellar chromosphere. The flux in the lines of N v (1240 Å), Si iii (1206 Å), Si iv (1400 Å), C ii (1335 Å) were measured by multiplying the flux in each spectral bin by the wavelength width of the bin. The line flux is then the sum of all flux bins within the wave range covered by the line (see equation 1 in France et al. 2018). The continuum at either side of the line was used to fit a linear continuum model and interpolate the continuum flux in the region of the line. This was then subtracted from the line flux. Line flux uncertainty was calculated by propagating the uncertainty on the flux from each spectral bin through the calculations. The Nv, Si iii and Si iv line fluxes are unaffected by ISM absorption. However, the C ii line (1335 Å) is affected. The C ii line fluxes in this catalogue are not adjusted to compensate for ISM absorption. It is recommended, as in France et al. (2018), that the other line fluxes are used when comparing activity levels of stars. Methods for estimating the line absorption are discussed in Redfield & Linsky (2004).

The above procedure is not appropriate for the Lyman-alpha line at 1215.67 Å because it does not account for the absorption by neutral hydrogen in the interstellar medium (ISM), that reduces the observed line flux. The flux measured directly from the spectrum is therefore unsuitable for calculating the intrinsic flux of the star or the irradiation of associated exoplanets by Lyman-alpha emission. An estimate of the intrinsic, unabsorbed by ISM, Lyman-alpha line flux was made based on the star’s observed X-ray flux using the empirical relations in Linsky, France, & Ayres (2013). These relations are based on a sample of nearby stars where both X-ray and Lyman-alpha flux have been observed, and the unabsorbed Lyman-alpha line has been reconstructed by modelling the ISM absorption (Wood et al. 2005) or using an iterative technique (France et al. 2012). The equations relating X-ray flux and unabsorbed Lyman-alpha flux are given in Table 2 of Linsky, France, & Ayres (2013) along with the A, B coefficients appropriate for F - G, K and M spectral types. For these Lyman-alpha unabsorbed flux estimates, the X-ray flux from XMM-Newton spectra was used. The absorbed Lyman-alpha line flux measurements are also included in the database for the purposes of assessing target feasibility for future UV observations. These are particularly relevant for studies designed to detect atmospheric evaporation using transit observations of the Lyman-alpha line.

2.5. Planet data

All the planet data included in our catalogue have been retrieved from The Extrasolar Planets Encyclopedia\(^5\). The exoplanets.eu database also includes some stellar parameters which we have incorporated into our database for completeness.

3. Exoplanets-A Database and tools

The catalogued data and the derived quantities discussed in Section 2 have been incorporated into a database, with an on-line user interface\(^6\), as discussed in this Section (see also Appendix A). The database is currently frozen. However, we are working towards a future upgrade that would include Gaia DR4 together with the new JWST observations and links to other spectrum repositories.

3.1. Database description

As one of the main milestones of the Exoplanets-A project, we have implemented an archive with all the relevant information about the 205 planets and their host stars from online archives and publications. This is a Virtual Observatory compliant archive built using a special version of the SVOCat\(^7\) publishing tool.

All the data are stored in a MySQL database and can be accessed both from its webpage\(^8\) or using Virtual Observatory protocols such as ConeSearch or SAMP. ConeSearch permits the user to restrict the search to objects in a cone centred around one position in the sky. SAMP allows the database to be used interactively with other VO applications (such as TOPCAT or Aladin) and exchange results with each other in a manner seamless to the user (see Figure A.1 of the appendix).

The database displays one row per exoplanet (205 rows) and 700+ data columns. This number includes stellar properties, error ranges, and references to the originating material (See Section 2). The database is divided into sections to make it easier to find specific types of data and, while there are some default settings for which columns, for example stellar properties, are displayed, one or more user-selected sections can easily be displayed. Broadly, the database consists of basic identification data in the sections “Names and Co-ordinates” and “Position distance Gaia DR2”. The Gaia section includes other useful stellar data such as T\(_\text{eff}\), colour and G magnitude.

Planet data (mass, radius, P\(_\text{orb}\), eccentricity etc.) are in the sections “Exoplanets.eu”. X-ray data are in several sections. The most important is “X-ray Exoplanets-A” which includes model fits and flux measurements from XMM pointed observations. Archival data has been gathered from 3XMM, that relies on automated fitting, and the Upper Limit server for ROSAT, Einstein and Exosat data. These are in sections “X-ray 3XMM”, “X-ray ROSAT” and “X-ray literature values” respectively. UV photometry is in sections “UV Galex” and “UV mag Swift XMM-OM”. HST UV spectra, including line-flux measurements, are in the “UV HST Exoplanets-A” section. For convenience when looking at the whole sample, the best available UV and X-ray data have been collected into single columns in the sections “UV preferred values” and “X-ray preferred values”. We list all the sections available in the DB, together with their provenance in Table 2.

The database has a web-based user interface allowing simple filtering and interrogation of the contents, and the option to download as CSV-, VOtable- or JSON-format files. In addition, thanks to hyperlinks within the database, it is possible to access all the information for any planet studied by the Exoplanets-A project in an individual page. These pages contain the summarised properties of the planetary system, the exoplanet, and its host star (See Appendix A for an example). In

---

\(^{5}\) http://exoplanet.eu/

\(^{6}\) http://svocats.cab.inta-csic.es/SVOCat/SVOCat-doc-2-2-excat2/

\(^{7}\) http://svo2.cab.inta-csic.es/vocats/exostars/

\(^{8}\) Example: (svo2.cab.inta-csic.es/vocats/exostars/cs.php?RA=172.33&DEC=-1.45&SR=1)
Table 2. Information provenance in the database.

<table>
<thead>
<tr>
<th>Section Name</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objects⁹</td>
<td>–</td>
</tr>
<tr>
<td>Names and Coordinates</td>
<td>SIMBAD</td>
</tr>
<tr>
<td>Exoplanet.eu</td>
<td>Encyclopaedia of exoplanetary systems</td>
</tr>
<tr>
<td>Exeter Library</td>
<td>Exoplanet transmission spectroscopy from Exeter University</td>
</tr>
<tr>
<td>Sweet-Cat</td>
<td>Sweet-Cat catalogue</td>
</tr>
<tr>
<td>Position Distance Gaia DR2</td>
<td>Gaia DR2</td>
</tr>
<tr>
<td>Optical IR mag SIMBAD</td>
<td>SIMBAD</td>
</tr>
<tr>
<td>Positions adjusted for PM</td>
<td>Derived by us</td>
</tr>
<tr>
<td>Available Data Summary</td>
<td>Derived by us</td>
</tr>
<tr>
<td>X-ray Data Available</td>
<td>XMM archive</td>
</tr>
<tr>
<td>X-ray Preferred Values</td>
<td>Derived by us</td>
</tr>
<tr>
<td>X-ray Literature Values</td>
<td>Literature</td>
</tr>
<tr>
<td>X-ray ExoplanetsA</td>
<td>Derived by us</td>
</tr>
<tr>
<td>X-ray 3XMM</td>
<td>XMM archive</td>
</tr>
<tr>
<td>X-ray ROSAT</td>
<td>ROSAT archive</td>
</tr>
<tr>
<td>UV Galex</td>
<td>Galex (MAST archive)</td>
</tr>
<tr>
<td>UV HST ExoplanetsA</td>
<td>Derived by us</td>
</tr>
<tr>
<td>UV HST Literature</td>
<td>Literature</td>
</tr>
<tr>
<td>UV mag Swift XMM OM</td>
<td>MAST/XMM archive</td>
</tr>
<tr>
<td>UV Preferred Values</td>
<td>Derived by us</td>
</tr>
<tr>
<td>Derived Quantities</td>
<td>Derived by us</td>
</tr>
<tr>
<td>Validation Flags</td>
<td>Derived by us</td>
</tr>
</tbody>
</table>

Notes. (⁹) This table is a single column with the object name. This is the unique ID by which a planet is recognised and crossmatched through the whole DB.

3.2. Validation of the database contents

We have carried out many general checks to ensure the validity of the data in various ways. We have especially investigated the consistency of values when multiple sources of data are available and compared our values with those found in other catalogues. For example, all XUV measurements were plotted to check that they fall within expected ranges for stellar coronal and chromospheric emission. Flux values from our own analysis were compared to values from the literature and from automatic extractions such as the 3XMM database to check that they are consistent. Twelve of the stars in this catalogue also appear in the X-ray flux catalogue of Spinelli et al. (2023). The flux values from

9 CASCADe (Calibration of trAnsit Spectroscopy using CAusal Data) is a python code used to calibrate the spectroscopic data for transiting exoplanets and to extract the transit or emission spectrum of the exoplanet. https://www.explore-exoplanets.eu/resource/cascade/

both independent analyses are in agreement within 1 σ, except for Wasp-43 and GJ 4370 which are within 2 σ. General checks were also carried out by comparing related quantities, such as spectral type and stellar effective temperature or planet orbital period and the flux received at the planet, searching for outliers and verifying that the data and derived values are correlated as expected.

3.3. Statistics

The 114 systems in our sample were selected because they had transit observations from either HST, Spitzer or both. This results in a sample of 205 planets, mostly with shorter orbital periods (as can be inferred from Fig 4), as close-in planets are more likely to be detected with the transit method. These are also the targets most likely to be suitable for transit spectroscopy and atmosphere studies with JWST. In fact, 31 of the planetary systems in the exoplanets-A DB are being observed with JWST.

For each star, photometry from the SWEET-CaT and Gaia catalogue were used to fit the spectral energy distributions (using exoVOSAI⁹). There was no IR excess in any object. The Gaia G magnitudes of our host stars range from 5.2 to 15.8 mag and the range of masses, radii and semi-major axis of the planets can be seen in Fig. 3 and Fig. 4. Figure 3 shows about 50 rocky planets in the lower left corner according to the models for different compositions derived by Seager et al. (2007). Figure 4 shows a clump in the top left part consisting of circularised Hot Jupiters. The limit of current detection capabilities is clearly shown by the lack of planets in the lower right part of the panel.

Figure 2 summarises the number of stars with XUV data available, according to spectral type. A total of 30/77 stars have X-ray/NUV flux measurements in the database. These stars have a total of 52/143 known planets. Figures 5 to 8 show the range of X-ray and NUV flux and luminosity values for the whole sample, plotted according to the host-star T_{eff}. The detected NUV flux ranges from 1.8 × 10^{-14} erg s^{-1} cm^{-2} (Fig.5). The intrinsic NUV luminosity calculated using the Gaia DR2 distances to the stars ranges from 3.2 × 10^{26} to 3.8 × 10^{22} erg s^{-1}, covering 6 orders of magnitude (Fig.6).

The X-ray detected flux ranges from 1.1 × 10^{-15} up to 1.6 × 10^{-13} erg s^{-1} cm^{-2} (Fig.7). The lowest flux target detected at
Masses and semi-major axes of our transiting exoplanets. Planets that have Spitzer or HST transit observations are shown in red or black respectively. Filled symbols are for planets with a value of orbital eccentricity in our database and symbol size scales linearly with eccentricity ranging from $\sim-0.7$.

The X-ray luminosity range is $1 \times 10^{36}$ up to $1.5 \times 10^{31}$ erg s$^{-1}$, covering five orders of magnitude (Fig. 8). The blue line shows the log $L_X/L_{bol} = -3$, saturation limit (Pizzolato et al. 2003). Stars below this line are no longer in the saturated X-ray emission phase, and the level of X-ray activity depends on the stellar rotation rate. Orange and green lines show the log $L_X/L_{bol}$ relation for -4 and -5 respectively. No targets more distant than 500 pc have been detected in X-ray observations (11 host stars in our sample have Gaia DR2 distances larger than 500 pc). Similarly, the NUV sample from Galex and Swift-UVOT covers a flux range of 4 orders of magnitude with very few targets detected at distances greater than 500 pc.

### 3.4. ExoVOSA: Fitting the observational data of exoplanets

In addition to the database, we have developed a new tool, exoVOSA$^{11}$, based in VOSA (VO SED Analyzer) software (Bayo et al. 2008), that aims at fitting the observational data of exoplanets. The tool is designed to perform the following tasks in an automatic manner: (i) read user photometry-tables; (ii) query several photometrical catalogs accessible through VO services (that increases the wavelength coverage of the data to be analyzed); (iii) query VO-compliant theoretical models (spectra) and calculate their synthetic photometry; (iv) perform a statistical test to determine which model reproduces best the observed data; and (v) use the best-fit model to provide bolometric luminosity (by integrating the photometry and using the known distance) and effective temperature, surface gravity and metallicity (from the model fit). ExoVOSA is currently available for planets detected by direct images and a limited collection of 13 theoretical grids, developed for brown dwarfs and non-irradiated massive planets to fit the spectral energy distribution of exoplanets.

### 4. Discussion

Here we examine what our database content may be able to tell us about the effects of the host star high-energy (XUV) emission on the exoplanet atmosphere. In particular, we can take advantage of the relatively large number of exoplanetary systems for which we have compiled both XUV and planetary data, compared with many previously reported studies. This allows us to explore the relations between stellar radiation and planetary radius and atmosphere type in more detail. Also, we are directly addressing the sample for which the Exoplanets-A project has performed a uniform analysis of the atmospheres.
4.1. The planet radius valley

The final configuration of an exoplanet, such as terrestrial, mini-Neptune or gas giant, is largely dependent on the type of atmosphere it retains. Planet formation theory suggests that rocky planets (0.1 - 5 M\(\oplus\)) form with a thick H-He envelope (Mizuno, Nakazawa, & Hayashi 1978; Lammer et al. 2014; Owen & Campos Estrada 2020) that would greatly increase their observed radius, and render them uninhabitable to any known form of life. However, many planets in our solar system and beyond do not have thick H-He envelopes. The photoevaporation process, which has been observed in several transiting systems (Poppenhaeger, Schmitt, & Wolk 2013; Ehrenreich et al. 2015), could fulfill the function of removing thick primordial H-He atmospheres from young planets, allowing a secondary thin atmosphere to form later. Stellar XUV radiation can play a role by causing heating and evaporation of atmospheres, and this process would be most effective for planets that are close-in to highly active stars (Hazra et al. 2022; Damasso et al. 2023; Ketzer et al. 2024). A measured or estimated stellar L_X is needed for modeling the atmospheric mass loss rate due to XUV irradiation, and thus determining if the rate is sufficient to completely remove the H-He envelope. Stellar L_X estimates are also needed in order to study the effects the wind could have on planetary magnetospheres and atmospheres (Ahuir, Brun, & Strugarek 2020).

Photoevaporation is not the only process that could potentially cause the radius gap. Planet formation simulations show that the distribution of material in the disk can produce a twin peak mass distribution where planets formed close to the star are lower mass, around 3 M\(\oplus\), while those beyond the ice line are rarely below 5 M\(\oplus\) (Venturini et al. 2020). The simulations showed that photoevaporation is also an important factor, and more study is needed to establish the relative importance of each process. It may be that the dominant process for determining planet radius distributions has some dependence on spectral type. Bonfanti et al. (2024) showed that M-dwarf planet systems have a slightly different slope of radius valley compared to FGK stars, indicating that processes like gas-poor formation and inward migration of water worlds may be more important for planets around M-dwarfs.

Atmospheric evaporation itself may also be driven by different processes. Modirrousta-Galian & Korenaga (2023) identified different regimes of atmospheric evaporation, where newly formed planets have atmospheric evaporation mainly driven by their high internal core temperature. XUV driven photoevaporation becomes important later, after the planet core has cooled. Boil-off driven by the stellar continuum should also be considered for low mass planets. Affolter et al. (2023) showed that hydrodynamic simulations are better able to reproduce the observed radius valley when the boil-off process is included. The XUV energy-limited approximation tends to underestimate atmospheric escape rates for low mass planets. It is likely that a combination of these processes affects each exoplanet to varying degrees.

Here we discuss an example of how the Exoplanet-A database can be used to explore the extent to which photoevaporation could be contributing to the radius valley. Using our sample of 205 exoplanets and associated XUV data, we investigate the evidence for XUV radiation having a detectable effect on planetary H-He atmospheres. The theory of primordial atmospheric removal by photoevaporation (Sekiya, Nakazawa, & Hayashi 1980a,b) predicts that there will be a lack of planets with radii \(\sim 2 R_{\oplus}\) (Owen & Wu 2013). Several studies have detected this gap in samples of exoplanets (e.g. Fulton et al. 2017; Van Eylen et al. 2018; Owen & Campos Estrada 2020). We start by investigating whether our sample also shows the radius gap.

Figure 9 shows the distribution of planet radii in the Exoplanets-A sample. The data are binned in logarithmic bins of 0.16 R\(\oplus\) to match the binning used for Fig 4 in Van Eylen et al. (2018) for comparison. Both samples show a twin peaked distribution, with the radius valley at \(\sim 2 R_{\oplus}\).

First, we consider whether the radius distribution is really multimodal. Although we see a clear dip in the sample at the ex...
The bandwidth in the KDE method is
the valley in this sample. This method smooths out noise in the
from the histogram, we used a Kernel density estimator (KDE)
analysis (Rosenblatt 1956; Parzen 1962) to find the location of
the valley in this sample. This method smooths out noise in the
data so that only significant peaks and dips are detected.

The minimum in the radius valley is located at 1.8 R\textsubscript{\oplus}. The
peak of the two distributions either side of the valley are at 1.5
R\textsubscript{\oplus} (super-Earths) and 2.4 R\textsubscript{\oplus} (mini-Neptunes). The bandwidth
used by the KDE method determines how sensitive the result
is to noise in the data. The bandwidth in the KDE method is
equivalent to the bin width for a histogram. A bandwidth that
is too large could smooth out real features. To check the effect
of bandwidth we used the "Cross Validation gridsearch" test im-
plemented in the Python library \texttt{sklearn} (Pedregosa, Varoquaux,
Gramfort et al. 2011). This method repeatedly splits the data
randomly into training and testing samples so that the validity of
the solution can be tested without having to remove a portion
of the training data for testing purposes. The cross-validation
found the best bandwidth is 0.078 that gives a radius valley lo-
cated at 1.79 R\textsubscript{\oplus} shown by the red line in Fig. 9. Using a KDE
with a larger bandwidth of 0.12 shifts the identified minimum to
slightly larger radius of 1.82 R\textsubscript{\oplus} as shown by the blue line in
Fig. 9.

Having confirmed the presence of the radius gap in our planet
population, we next investigate what could have caused it. The
photoevaporation model (e.g. Owen & Campos Estrada 2020)
predicts a radius gap at this range because the planet radius deter-
mines how strongly a planet can hold on to its H-He atmosphere.

Low-mass planets with a core at or below the 1.8 R\textsubscript{\oplus} limit may
lose their atmosphere via a rapid hydrodynamical process if sub-
jected to stellar XUV radiation, so after several Gyr, all that
remains is a stripped core (e.g. Becker et al. 2020). Planets with
a core above the ~1.8 R\textsubscript{\oplus} limit have a stronger gravitational po-
tential and are able to retain some of their envelope. They are
more likely to remain with a radius larger than ~1.8 R\textsubscript{\oplus}, since
only a small mass of retained H-He atmosphere can greatly in-
crease the observed planetary radius. There are four planets in
our sample that appear to be within the radius gap, between 1.7
and 2 R\textsubscript{\oplus}. These are 55 Cnc e, Kepler-9 d, Kepler-20 b and
Kepler-11 b.

We investigate the likely evaporation processes applicable
to the planets. The rate of evaporation, and whether or not it
will be sufficient to completely remove the primordial H-He at-
mosphere, depends on two main factors. The first factor is the
planet’s gravitational potential energy, that determines the es-
cape regime it will be in if subjected to XUV radiation. For ex-
ample, rapid hydrodynamic escape, or slow Jeans escape. The
second factor is the XUV flux incident at the planet that deter-
mines the rate of evaporation, given the escape regime applicable
to that particular planet. Fig. 10 shows the log gravitational po-
tential energy of the planets which have observed X-ray flux.

The observed X-ray and estimated EUV luminosity are added
to get the combined XUV luminosity. The flux at the planet is then calculated from the stellar XUV luminosity and
the planet semi-major axis. This assumes the effect of orbital ec-
centricity is negligible.

There are 30 planets to the left of the red line which indicates
that they have weak enough gravity so that atmospheric escape
would take place via the rapid hydrodynamical loss process. To
the right of the red line, only the slower Jeans escape process
would be possible due to the planets stronger gravitational poten-
tial energy. The markers are plotted as circles for planets below
the ~1.8 R\textsubscript{\oplus} radius gap. Planets with a larger radius are plotted
as crosses and are planets that may still have a remaining primor-
dial atmosphere undergoing evaporation. Those planets plotted
as circles have likely had their atmospheres entirely evaporated.

Fig. 10 shows that, for this sample, is mostly the planets re-
ceiving less XUV flux that have low radius. One possible expla-
nation could be that they are in older systems where the evap-
oration process has already taken place over a long period, and
the stars X-ray luminosity has declined due to spin down (e.g.
Wright et al. 2011; Johnston 2020). The majority of planets in
the lower flux region belong to the \textit{Trappist-1} system, which is
relatively old at 7.6±2.2 Gyr (Burgasser & Mamajek 2017), and
is known to have an X-ray luminosity of L\textsubscript{x}\textasciitilde2\texttimes10\textsuperscript{-4}
\pi R\textsubscript{\oplus} (Wheatley et al. 2017) that is lower than the typical saturation
limit of 10\textsuperscript{-3}. Planets receiving higher XUV flux are more likely
to be orbiting active younger stars, assuming a sample with a
more similar spread of orbital radius and spectral type, so the evapo-
ration process may not yet have had time to remove the whole
envelope. More work is needed to establish accurate ages for
host stars to be able to investigate this question.

An important caveat to this analysis is that it does not include
Roche lobe effects, that can greatly increase the mass loss rate
for planets very close to their host star. For example, WASP-121
b has a much higher rate of atmospheric loss than Fig.10 would
indicate (Koskinen et al. 2022; Huang et al. 2023).

4.2. Evidence for the photoevaporation model from
multi-planet systems

The present day radius of a planet is a result of the cumulative
mass loss that has taken place throughout its evolution. One
way to investigate whether this could be the cause of the radius
valley is to estimate the total mass lost over the lifetime of the
Despite many improvements to atmospheric mass loss rates based on grids of hydrodynamic simulations (Kubyshkina et al. 2018; Krenn et al. 2021) are now available. Stellar XUV radiation can also potentially cause loss of liquid water from planets in the habitable zone of highly active stars (e.g. Wheatley et al. 2018; Krenn et al. 2021). Therefore, populations of stars that are only a few million years old have a spread in rotation rate, and thus activity level, of an order of magnitude. After a few billion years, the rotation rates converge, rendering it currently impossible to know if the star was a fast or slow rotator earlier in its history (Johnstone, Bar- tel, & Güdel 2021). So, while the current mass-loss rate can be estimated, the star’s XUV evolution, and the long-term effect of photoevaporation on the planet cannot be determined with accuracy. To avoid this limitation, we use the multi-planet systems in our sample to investigate the comparative mass loss, which negates the need to know the full stellar evolutionary history. Owen & Campos Estrada (2020) developed the method of using multiplanet systems to test the photoevaporation model. This method relies on comparing planets above and below the radius gap in the same planetary system, and has the advantage of rendering it unnecessary to know the complete XUV radiation history of the star, since both planets have been subjected to the same XUV history, once the planetary distances from the star have been taken into account. In our sample there are 14 systems with multiple planets straddling the radius gap that could potentially be used as a test of the photoevaporation model. Eight of these systems are not in the samples tested in Owen & Campos Estrada (2020), and some systems have additional planets. For example, Kepler-102f is included in our sample. In Fig.11, the systems that have planets above and below the radius gap are plotted as a function of the orbital period. Planets with a radius less than 1.8 $R_\oplus$ are plotted in blue and greater than 1.8 $R_\oplus$ in grey. The marker sizes are scaled according to the planet radius. The method considers a planetary system as a whole, and relies on assuming that the super-Earth is below the radius gap because it received just enough XUV flux to completely evaporate its atmosphere. The mass-loss timescale for the mini-Neptune must be longer than this, since it did not lose all of its envelope. After the difference in received XUV flux is taken into account, by comparing the planets’ orbital periods (and hence star-planet distance), the only remaining factor that would increase the mass loss timescale of the mini-Neptune is its mass, and hence its stronger gravity that could retain its atmosphere. Equation 4 (Owen & Campos Estrada 2020) gives the minimum mass required for the mini-Neptune ($M_g$) to have retained its primordial atmosphere. If the measured planet mass is greater than this, the system is compatible with the photoevaporation model.

\[
M_g \geq 5.1 M_{\oplus} \left( \frac{R_g}{1.5 R_{\oplus}} \right)^{\frac{1}{2}} \left( \frac{a_g}{a} \right) \]  

(4)

In contrast, if the planet above the radius gap has a lower mass than the minimum for atmosphere retention, then it must have retained its primordial atmosphere because of some factor that is not accounted for in the photoevaporation model, such as orbit migration or planetary magnetosphere, or the super-Earth lost its atmosphere due to some other process than photoevaporation. In Equation 4, $R_g$ is the radius of the rocky planet, and $a_g$ the orbital distance.
The 14 planetary systems were input to the code publicly available at https://github.com/jo276/EvapMass. The input includes stellar and planetary properties (radius, orbital period, etc.). The output from the program is the minimum required mass loss timescale that would enable “e” to have a longer mass loss timescale than the planet below the radius gap. However, a small increase in Pec could be found that would enable “e” to have a longer mass loss timescale than the planet below the radius gap. The low radius planet would be easily stripped of its envelope, and the strength of photoevaporation required to do that would have no significant effect on the planet above the radius gap, regardless of its mass. In general, we find that most systems in our sample are compatible with the photoevaporation model, but K2-3 could be a notable exception.

Systems where the larger radius planet does not have a longer mass loss timescale than the planet below the radius gap are marked with as “No Solution” in Table 3. These systems are incompatible with the photoevaporation model.

The K2-3 system seems to be the clearest example of a contradiction to the photoevaporation model. The inner planet “b” is above the radius gap. The 2 exterior planets “c” and “d” are both below the radius gap (see bottom row of Fig. 11). Planet b does not have enough mass to have retained it’s primordial atmosphere, given that it was subjected to the same XUV irradiation history as planet c and d. This could indicate that some factor not included in the model has increased the mass loss timescale of planet “b”, such as inward migration, or a strong magnetosphere that has protected the atmosphere. A similar analysis by Diamond-Lowe et al. (2022) reached the same conclusion.

There were 5 planet combinations that did not place any constraint on the minimum mass. These are recorded as “LM” in Table 3. “LM” (lower mass) refers to cases where no lower mass bound for the gas planet’s core could be found in the range > 0.1M⊕ (See Fig 1 Owen & Campos Estrada (2020)). This means that even a planet with a mass < 0.1M⊕ would have a longer mass loss timescale than the planet below the radius gap.

In addition, we have used the multiplanet systems in our sample to test the photoevaporation model. Only one system, K2-3, out of 14 systems poses a contradiction to the photoevaporation model. The fact that the inner planet of the system is above the radius gap and the two exterior planets are both below the radius gap are marked with an asterisk in Table 3. These systems are incompatible with the photoevaporation model. The K2-3 system seems to be the clearest example of a contradiction to the photoevaporation model. The inner planet “b” is above the radius gap. The 2 exterior planets “c” and “d” are both below the radius gap (see bottom row of Fig. 11). Planet b does not have enough mass to have retained it’s primordial atmosphere, given that it was subjected to the same XUV irradiation history as planet c and d. This could indicate that some factor not included in the model has increased the mass loss timescale of planet “b”, such as inward migration, or a strong magnetosphere that has protected the atmosphere. A similar analysis by Diamond-Lowe et al. (2022) reached the same conclusion.

There were 5 planet combinations that did not place any constraint on the minimum mass. These are recorded as “LM” in Table 3. “LM” (lower mass) refers to cases where no lower mass bound for the gas planet’s core could be found in the range > 0.1M⊕ (See Fig 1 Owen & Campos Estrada (2020)). This means that even a planet with a mass < 0.1M⊕ would have a longer mass loss timescale than the planet below the radius gap.

In general, we find that most systems in our sample are compatible with the photoevaporation model, but K2-3 could be a notable exception.

5. Conclusions

We have compiled a catalogue of host-star characteristics that includes basic properties for all 114 stars associated with the exoplanets in the ExoplanETS-A sample. It contains information on the optical and IR bandpasses for almost all the stars plus X-ray detections for ~ 25%, UV photometry for ~ 60%, and UV spectra for ~ 25% of the stars.

With this catalogue we have implemented a database that includes X-ray and OHP spectra, TESS light curves and other useful information on top of the catalogue itself. We have also implemented the tool exoVOSA that is able to fit the spectral energy distribution of exoplanets using a collection of theoretical grids, developed for brown dwarfs and non-irradiated massive planets.

We have used this database information to study the effects of the host star high-energy (XUV) emission on the exoplanet atmosphere. In particular, we have studied the planet radius-valley which we find is located at 1.8R⊙, in agreement with previous studies. In addition, we have used the multiplet systems in our sample to test the photoevaporation model. Only one system, K2-3, out of 14 systems poses a contradiction to the photoevaporation model. The fact that the inner planet of the system is above the radius gap and the two exterior planets are both below the radius gap may be indicating that an inward migration happened or that the planet has a strong magnetosphere that has protected the atmosphere. In any case, it would seem that some factor or a mixture of factors not included in the photoevaporation model has increased the mass-loss timescale of the inner planet.

The host star information included in our database complements the uniform set of exoplanet HST and Spitzer visible/IR spectra and associated retrievals of atmospheric properties produced by the ExoplanETS-A project. The exoplanet and stellar resources compiled and generated by ExoplanETS-A form a...
Table 3. Minimum mass values for planets above the radius gap.

<table>
<thead>
<tr>
<th>Planet above radius gap</th>
<th>Radius ( (R_\oplus) )</th>
<th>( P_{\text{orb}} ) (days)</th>
<th>Measured mass ( (M_\oplus) )</th>
<th>Minimum mass prediction from each planet below 2 ( R_\oplus )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler-102 e</td>
<td>2.22</td>
<td>16.15</td>
<td>8.93</td>
<td></td>
</tr>
<tr>
<td>Kepl-68 c</td>
<td>0.93</td>
<td>9.6</td>
<td>5.97</td>
<td></td>
</tr>
<tr>
<td>Kepler-49 b</td>
<td>2.69</td>
<td>7.2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Kepler-49 c</td>
<td>2.58</td>
<td>10.91</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Kepler-125 b</td>
<td>2.37</td>
<td>4.16</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Kepler-11 c</td>
<td>2.87</td>
<td>13.03</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Kepler-11 d</td>
<td>3.12</td>
<td>22.69</td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>Kepler-11 e</td>
<td>4.19</td>
<td>31.99</td>
<td>9.53</td>
<td></td>
</tr>
<tr>
<td>Kepler-11 f</td>
<td>2.49</td>
<td>46.69</td>
<td>1.99</td>
<td></td>
</tr>
<tr>
<td>Kepler-11 g</td>
<td>3.67</td>
<td>118.38</td>
<td>301.9</td>
<td></td>
</tr>
<tr>
<td>HD 3167 c</td>
<td>3.02</td>
<td>29.85</td>
<td>9.78</td>
<td></td>
</tr>
<tr>
<td>Kepler-10 c</td>
<td>2.35</td>
<td>45.29</td>
<td>7.36</td>
<td></td>
</tr>
<tr>
<td>Kepler-20 c</td>
<td>3.05</td>
<td>10.85</td>
<td>12.75</td>
<td></td>
</tr>
<tr>
<td>Kepler-20 d</td>
<td>2.74</td>
<td>77.61</td>
<td>10.06</td>
<td></td>
</tr>
<tr>
<td>K2-3 b</td>
<td>2.17</td>
<td>10.05</td>
<td>6.47</td>
<td></td>
</tr>
<tr>
<td>Kepler-9 b</td>
<td>8.20</td>
<td>19.22</td>
<td>43.5</td>
<td></td>
</tr>
<tr>
<td>Kepler-9 c</td>
<td>8.29</td>
<td>38.97</td>
<td>29.9</td>
<td></td>
</tr>
<tr>
<td>Kepler-18 c</td>
<td>5.48</td>
<td>7.6</td>
<td>17.20</td>
<td></td>
</tr>
<tr>
<td>Kepler-18 d</td>
<td>6.97</td>
<td>14.86</td>
<td>16.29</td>
<td></td>
</tr>
<tr>
<td>Kepler-126 d</td>
<td>2.51</td>
<td>100.28</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Kepler-127 c</td>
<td>2.39</td>
<td>29.39</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Kepler-218 c</td>
<td>3.13</td>
<td>44.70</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Kepler-218 d</td>
<td>2.66</td>
<td>124.5</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Notes. The planets listed in the left half of the table are above the radius gap and have an observed mass listed in column 4. These can be compared to their minimum mass predicted from the planets below the period gap (right hand section of the table). Systems marked “No Solution” are not compatible with the photoevaporation model. Note that the mass values in the right half of the table are predictions for the mass of planets in the left half, not masses of the planets in the right half. Minimum mass values with an asterisk had estimated solar mass values used in the calculation. Planets that do not constrain the minimum mass are marked LM. The minimum masses are estimated using the Owen & Campos Estrada (2020) code.

References

Appendix A: Examples of database usage:
Visualising the most important information for a planet or host star

A summarised version of the planet, the whole system, and the host-star information can be accessed through individual pages by means of an hyperlink on the planet name (see Fig.A.1). There is an individual page per planet\(^{12}\). In the upper part of the page there is a summary of the star properties and main magnitudes, and the system planets parameters. Then comes some external data for the host star. These data include the \textit{TESS} light curves, and direct access to some \textit{TESS} pipeline files for direct download, and several links that lead to predefined queries in the OHP archives for the available ELODIE and SOPHIE spectra and CCF catalogues. At the bottom of the individual webpage we find the information on the planet. First there is a selection of the planet parameters from the database and then an interactive visualisation of the exoplanet transit depth records from NASA Exoplanet Archive (2850 records are available). Our own CAS-CADe reduction is also available here to visualise and to download (see Figure A.2). Finally there is a table summarising and with direct access to reference papers, facility and instrument of the observations.

\(^{12}\) An example can be seen here: http://svo2.cab.inta-csic.es/vocats/exostars/fichas/?id=222
Fig. A.1. Default look of the database webpage. On the upper part grey rectangles with plus symbols are the different sections from where the specific fields can be marked to be displayed. Marked in red are the link to individual pages for a planet, the download available formats and the button to send the data to other VO applications.

Fig. A.2. Example of the spectra visualisation for planet HAT-P-12b with the Exoplanets-A reduction shown in cyan.