TOPCAT and Gaia XP Spectra

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Applications WG
IVOA Interop
Online

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Working with array-valued data:

- DataLink refresher, Gaia DR3 as example
- Using TOPCAT with DataLink services
  - Example: DR3 XP spectra using Activation Actions
- Using TOPCAT with array-valued columns
  - Example: DR3 XP spectra in table rows
- Summary of relevant TOPCAT/STILTS features
Gaia **XP Sampled Spectra** data product, new in Gaia DR3

- Spectral data from BP + RP low-resolution spectrometry instruments
- Reconstructed from XP Continuous Spectra (coefficients)
- Available for 34M / 1.8G sources at DR3
- 343-row wavelength, flux, flux_error tables
- Wavelength values same for all sources

Access

- Delivered only via DataLink from ESA TAP service
- Available in other forms elsewhere

<table>
<thead>
<tr>
<th>wavelength $nm$</th>
<th>flux $Wm^{-2}nm^{-1}$</th>
<th>flux_error $Wm^{-2}nm^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 336.0</td>
<td>1.8571556E-17</td>
<td>9.309491E-18</td>
</tr>
<tr>
<td>2 338.0</td>
<td>1.0335697E-17</td>
<td>7.1697286E-18</td>
</tr>
<tr>
<td>3 340.0</td>
<td>8.157212E-18</td>
<td>5.6923542E-18</td>
</tr>
<tr>
<td>4 342.0</td>
<td>1.1108474E-17</td>
<td>5.036669E-18</td>
</tr>
<tr>
<td>5 344.0</td>
<td>1.3550346E-17</td>
<td>4.7585802E-18</td>
</tr>
<tr>
<td>6 346.0</td>
<td>1.1722847E-17</td>
<td>4.8270174E-18</td>
</tr>
<tr>
<td>7 348.0</td>
<td>8.0488636E-18</td>
<td>5.0007076E-18</td>
</tr>
<tr>
<td>8 350.0</td>
<td>7.61149E-18</td>
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<tr>
<td>9 352.0</td>
<td>1.1499628E-17</td>
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<tr>
<td>10 354.0</td>
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<td>11 356.0</td>
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<td>...</td>
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<tr>
<td>341 1016.0</td>
<td>4.218802E-16</td>
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<tr>
<td>342 1018.0</td>
<td>4.2090065E-16</td>
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<tr>
<td>343 1020.0</td>
<td>4.3125362E-16</td>
<td>5.3213895E-17</td>
</tr>
</tbody>
</table>
Multiple “ancillary” data products are associated with each DR3 source

- These items are bulky (array-valued) and in general not available in the database (by direct ADQL query)
- Each source may have none, some or all of 6 items:
  - **XP sampled spectrum**, XP continuous spectrum, RVS spectrum, epoch photometry, MCMC gspht, MCMC MSC
- There is a (DataLink) **Links Table** associated with each gaia_source table row
  - Each row describes one ancillary product
- How to find the Links Table?
  - **Either:** From service-specific documentation
    - Gaia DR3 links table URL is https://gea.esac.esa.int/data-server/datalink/links?ID=<designation>, where <designation> looks like Gaia+DR3+3034394744320 (see DR3 docs)
  - **Or:** Use a (DataLink) **Service Descriptor**
    - Returned with result VOTable from suitable VO queries
    - Maps result table row to Links Table URL (using some ID value in the table)
    - For ESA Gaia DR3, query SELECT must include designation column (to use as ID)

<table>
<thead>
<tr>
<th>ID</th>
<th>description</th>
<th>semantics</th>
<th>content_type</th>
<th>access_url</th>
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</thead>
<tbody>
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<td>Gaia DR3 30343944744320</td>
<td>MCMC MSC, source Gaia DR3 30343944744320</td>
<td>#this</td>
<td>application/x-votable+xml</td>
<td><a href="https://gea.esac.esa.int/data-server/data?ID=Gaia+DR3+3034394744320&amp;RETRIEVAL_TYPE=MCMC_MSC">https://gea.esac.esa.int/data-server/data?ID=Gaia+DR3+3034394744320&amp;RETRIEVAL_TYPE=MCMC_MSC</a></td>
</tr>
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<td>Gaia DR3 30343944744320</td>
<td>XP mean sampled spectra, source Gaia DR3 30343944744320</td>
<td>#this</td>
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<td><a href="https://gea.esac.esa.int/data-server/data?ID=Gaia+DR3+3034394744320&amp;RETRIEVAL_TYPE=XP_SAMPLED">https://gea.esac.esa.int/data-server/data?ID=Gaia+DR3+3034394744320&amp;RETRIEVAL_TYPE=XP_SAMPLED</a></td>
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<tr>
<td>Gaia DR3 30343944744320</td>
<td>XP mean continuous spectra, source Gaia DR3 30343944744320</td>
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<td>application/x-votable+xml</td>
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<tr>
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<td>RVS mean spectra, source Gaia DR3 30343944744320</td>
<td>#this</td>
<td>application/x-votable+xml</td>
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**Note:** Gaia DR3 is just one (important) example — many other services use DataLink in the same way
TOPCAT and DataLink

TOPCAT features for working with DataLink services:

• Reports Service Descriptors in Parameters Window
• Provides Activation Actions to view/use Links Tables when parent table row is **activated**
  ▶ **Invoke Service** action displays Links Table located by service descriptor
  ▶ **View Datalink Table** action displays Links Table given explicit root URL

• Displayed Links Table has options to follow the links in it:
  ▶ Select data product of interest
  ▶ Specify an action on that data product (e.g. Load table into TOPCAT, Plot table columns, ...)
  ▶ When next parent table row (source) is activated, the corresponding row is selected, and action can be auto-invoked
Example: DataLink and Activation Actions

View XP Sampled spectra for points in a plot of interest

Query `gaia_source` table to plot HR diagram of nearby stars:

```sql
SELECT designation, source_id, ra, dec, parallax, bp_rp, phot_g_mean_mag,
       phot_g_mean_mag + 5*log10(parallax/100) AS mag_g
FROM gaiadr3.gaia_source
WHERE parallax > 10
  AND parallax_over_error > 10
  AND phot_bp_mean_flux_over_error > 10
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  AND astrometric_excess_noise < 1
  AND has_xp_sampled = 'true'
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- Select on `has_xp_sampled` to ensure spectra are available
- Must SELECT `designation` to get Service Descriptor

View Service Descriptor in **Parameters Window**

Set up **Activation Action**

- Select checkbox for **Invoke Service**
- Service Action is **View DataLink Table**
- Select **XP mean sampled spectra** row of DataLink table
- Configure to **Plot Table** on DataLink load and **Auto-Invoke**
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Working with multiple spectra

- DataLink works fine for looking at one spectrum at a time
- Sometimes you want to manipulate (e.g. visualise) multiple spectra at once
- To do that in TOPCAT you need array-valued columns
  - One spectrum per row
  - `fluxes` column and maybe matching `wavelengths` and `flux_errors` columns (same number of elements in each array)

How to get tables with spectra as array columns? Options for Gaia DR3 XP spectra:

- Use STILTS `arrayjoin` command (form of spectrum URLs is from [ESA DataLink service docs](https://gea.esac.esa.int/data-server/data?RETRIEVAL_TYPE=XP_SAMPLED&RELEASE=Gaia+DR3&ID=source_id)) — requires STILTS $\geq$ v3.4-6
  - For each row, adds $N$-element array-valued columns `wavelength`, `flux`, `flux_error` from $N$-row downloaded XP table
  ```bash
  stilts arrayjoin in=dr3-sources.vot \
  atable="https://gea.esac.esa.int/data-server/data?RETRIEVAL_TYPE=XP_SAMPLED&RELEASE=Gaia+DR3&ID="+source_id' \
  icmd=progress \
  out=sources-with-xp.fits
  ```
- ARI-Gaia TAP service has table `gaiadr3.xp_sampled_mean_spectrum` (though ESA Gaia TAP service does not)
  - Array-valued `flux` and `flux_error` columns are available in the database
    ```sql
    SELECT source_id, ra, dec, parallax, flux, flux_error, ... 
    FROM gaiadr3.xp_sampled_mean_spectrum 
    NATURAL JOIN gaiadr3.gaia_source 
    WHERE ...
    ```
  - Can use expression `sequence(343,336.0,2)` for wavelength array
- See also `gedr3spec` tables in GAVO DC TAP service (lower resolution spectra, but for more sources)
Example: Spectra as Arrays

Get some White Dwarf spectra

```sql
SELECT source_id, bp_rp, phot_g_mean_mag + 5 * log10(parallax/100) AS g_abs
FROM gaiadr3.gaia_source
WHERE parallax > 10 AND parallax_over_error > 10
  AND phot_bp_mean_flux_over_error > 10 AND phot_rp_mean_flux_over_error > 10
  AND astrometric_excess_noise < 1
  AND has_xp_sampled = 'true'
  AND bp_rp BETWEEN -0.63 AND 1.21
  AND phot_g_mean_mag + 5 * log10(parallax/100) BETWEEN 7.4 AND 15.5

stilts arrayjoin in=wd_hrd.fits icmd=progress out=wd_spectra.fits \
atable="https://gea.esac.esa.int/data-server/data?RETRIEVAL_TYPE=XP_SAMPLED&RELEASE=Gaia+DR3&ID=source_id"
```

View them using the XYArray plot

- Use array functions to normalise them
- If X Values are blank, array index is used instead
- Plot mean spectra etc using StatLine/StatMark form
- Linked views using subsets
- To highlight activated row, use Activated subset
- To select single/multiple rows from plot, use Handles layer

(most of these features require recent versions)
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SELECT source_id, bp_rp, phot_g_mean_mag + 5*log10(parallax/100) AS g_abs
FROM gaiadr3.gaia_source
WHERE parallax > 10 AND parallax_over_error > 10
AND phot_bp_mean_flux_over_error > 10 AND phot_rp_mean_flux_over_error > 10
AND astrometric_excess_noise < 1
AND has_xp_sampled = 'true'
AND bp_rp BETWEEN -0.63 AND 1.21
AND phot_g_mean_mag + 5*log10(parallax/100) BETWEEN 7.4 AND 15.5
```

```
stilts arrayjoin in=wd_hrd.fits icmd=progress out=wd_spectra.fits \
atable="https://gea.esac.esa.int/data-server/data?RETRIEVAL_TYPE=XP_SAME"
```

View them using the XYArray plot

- Use array functions to normalise them
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Example: Spectra as Arrays

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Summary: TOPCAT Features for Array Data

Data Access:

- Activation Actions
  - **Invoke Service** understands Service Descriptors
  - **View Datalink Table** using `{links}` Endpoint and ID column — *New!*
- Auto-invoke row from DataLink table (Load, Plot, Send, ...)
- STILTS `arrayjoin` command — *New!*

Visualisation:

- XYArray plots
- Activation Subset — *New!
- XYArray Handle plot layer — *New!
- StatMark/StatLine and ArrayQuantile plot layers — *New!*

Array manipulation

- Array collapse functions: mean, median, minimum, maximum, quantile, ...
- Array combination functions: multiply, divide, add, subtract, ...
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