The Missing Link: Connecting Exoplanets and Galactic Chemical Evolution via Stellar Abundances

David Coria\textsuperscript{1}, Ian Crossfield\textsuperscript{1}, Joshua Lothringer\textsuperscript{2}

\textsuperscript{1}Department of Physics & Astronomy, University of Kansas, Lawrence, KS, USA
\textsuperscript{2}Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD, USA
Overview

1. Discuss the significance of stellar abundances

2. Data Processing + Isotopic Abundance calculations

3. Next Steps
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1. Discuss the significance of stellar abundances

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3. Next Steps
Why study abundances?

Stellar chemical properties carry an ABUNDANCE of info!

1) Elemental enrichment helps us study: star formation, age constraints, interior modeling, planetary system formation, planet habitability

2) Can compare stellar abundances to: local ISM, YSOs, and GCE models
Elemental Abundances: C & O

C/O Ratio: volatile elements; ice + gas + rock chemistry; exoplanet atmospheres

Volatile Analysis via Transmission Spectroscopy

WASP-121b: Stratosphere Detection

Credit: Christine Daniloff/MIT, Julien de Wit

Credit: Engine House VFX, At-Bristol Science Centre, University of Exeter.
Elemental Abundances: Mg & Si

Mg/Si Ratio: rock chemistry, geology; exoplanet interiors

Olivine: \((\text{Mg}_2, \text{Fe}_2)\text{SiO}_4\)

Pyroxene: \(X(Y\text{Si,Al})_2\text{O}_6\)
\(X = \text{Ca, Na, Fe, Mg}\)
\(Y = \text{Cr, Al, Fe, Mg, Co …}\)

Differentiation!
It’s important to look for C/O and Mg/Si ratios significantly different from what we know!!!
Why study abundances?

Stellar chemical properties carry an ABUNDANCE of info!

1) Elemental enrichment helps us study: star formation, age constraints, interior modeling, planetary system formation, planet habitability

2) Can compare stellar abundances to: local Interstellar Medium (ISM), Young Stellar Objects (YSOs), and Galactic Chemical Evolution (GCE) models
Galactic Chemical Evolution (GCE) Models

M-Dwarfs (Crossfield+ 2019):

Young Stellar Objects:

Kobayashi (2011) GCE Model:

Proposed GCE Correction:
Short-Term Goal: Isotopic Abundances

High-resolution spectroscopy allows for isotopic abundance analysis; even in M-dwarfs with low S/N spectra + molecular line contamination!!!

Task: Calculate CO isotopic abundances in 6 solar twin stars AND:
moving group stars, cool binaries, field M-dwarfs, JWST-targeted exoplanet host stars
Why Solar Twins?

What star do we know the BEST???

Hint: Name rhymes with “Fun”

Generating model spectra is far easier for solar twins than for other stars!

Solar twins are hot enough that we don’t see the molecular absorption present in cooler KM dwarfs
### Solar Twin Sample

**O0\(^{\text{hot}}\) B A F G K M9\(^{\text{cool}}\)**

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
<th>(T_{\text{eff}}) (K)</th>
<th>Radius (xSol)</th>
<th>Age (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST #1</td>
<td>G5V</td>
<td>5838</td>
<td>0.96</td>
<td>2.42</td>
</tr>
<tr>
<td>ST #2</td>
<td>G4V</td>
<td>5758</td>
<td>0.95</td>
<td>5.51</td>
</tr>
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<td>ST #3</td>
<td>G8V</td>
<td>5848</td>
<td>1.0</td>
<td>1.01</td>
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<tr>
<td>ST #4</td>
<td>G2V</td>
<td>5683</td>
<td>0.96</td>
<td>3.67</td>
</tr>
<tr>
<td>ST #5</td>
<td>G2V</td>
<td>5814</td>
<td>1.03</td>
<td>3.09</td>
</tr>
<tr>
<td>ST #6</td>
<td>G3V</td>
<td>5694</td>
<td>1.04</td>
<td>6.66</td>
</tr>
<tr>
<td>Sun</td>
<td>G2V</td>
<td>5780</td>
<td>1.0</td>
<td>4.603</td>
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</table>

*Dos Santos+ 2016

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**Normalized Flux**

![Solar Twin Spectra](image)

**Wavelength (um)**
Calculating Isotopic Abundances: Step 1

Goal: Measure isotopologue abundances ($^{12}$C$^{16}$O, $^{13}$C$^{16}$O, $^{12}$C$^{18}$O) to determine isotopic abundance ratios ($^{12}$C/$^{13}$C, $^{18}$O/$^{16}$O)

Note: Isotopologue is to *Molecule* what Isotope is to *Atom*
*Different mass numbers

Step 1: Identify CO absorption lines!!!
$^{12}$CO, $^{13}$CO, and $^{18}$O lines from HITRAN

107 different CO lines in this MIR region!!!

- 41 $^{12}$CO lines
- 34 $^{13}$CO lines
- 32 $^{18}$O lines
Identify Useable Lines

Remove lines obscured by tellurics and lines that are out of our instrument’s range.
Identify Useable Lines

Remove lines that are dominated by stronger spectral features!

Solar Twin #2 Reduced Spectrum

Solar Twin #4 Reduced Spectrum
Calculating Isotopic Abundances: Step 2

Step 2: Snip the CO absorption features out of the solar twin spectrum and stack to create a single line profile

Step 2b: Repeat for solar models w/ 0x, 1/3x, 1x, and 3x solar CO
Snipping Out the Absorption Features

Full Spectrum: ___________________________  Snip: ___________________________

[Graph showing absorption lines in the solar spectrum]
Creating a Single Line Profile

Stacked Absorption Lines ($^{13}\text{CO}$)

Wavelength to Velocity:

$$\nu = \frac{\lambda - \lambda_0}{\lambda_0} c$$

Sample Single Line Profile: ($^{13}\text{CO}$)
Step 3: Compare single line profiles (Solar Twin vs. Models)
$^{13}$CO Abundance Plots!!!

ST #1: Single Line Profile

ST #2: Single Line Profile

Coria+ in prep.
$^{13}$CO Abundance Plots!!!

ST #3: Single Line Profile

ST #4: Single Line Profile

Coria+ in prep.
$^{13}\text{CO}$ Abundance Plots!!!

ST #5: Single Line Profile

ST #6: Single Line Profile

Coria+ in prep.
Step 4: Derive final abundance values using chi-squared fit tests
Using Chi-Squared Fit Tests for a Final Value

ST #4: Single Line Profile

![Normalized Flux Intensity vs Velocity](image1)

![Chi-Squared Fit: Solar Twin 4](image2)
### Final Abundances + Additional Parameters

#### ***Table from Earlier***

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<table>
<thead>
<tr>
<th>Star</th>
<th>log(Fe/H)</th>
<th>log(C/H)</th>
<th>log(O/H)</th>
<th>$^{13}\text{CO}$ (dex)</th>
<th>$^{18}\text{O}$ (dex)</th>
<th>$^{13}\text{CO}$ (dex)</th>
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<td>-0.08</td>
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<td>?</td>
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<td>?</td>
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<tr>
<td>ST #3</td>
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<td>?</td>
<td>0.15</td>
<td>?</td>
<td>?</td>
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<tr>
<td>ST #4</td>
<td>0.036</td>
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<td>-0.02</td>
<td>0.12</td>
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<td>?</td>
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<tr>
<td>ST #5</td>
<td>0.056</td>
<td>0.02</td>
<td>0.03</td>
<td>-0.13</td>
<td>?</td>
<td>?</td>
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<td>ST #6</td>
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<td>0.12</td>
<td>?</td>
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<tr>
<td>Sun</td>
<td>-0.477?</td>
<td>-0.358?</td>
<td>-0.326?</td>
<td>0.0</td>
<td>0.0</td>
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*Dos Santos+ 2016, Brewer & Fischer 2016

**Metallicity**

- log(Fe/H)
- log(C/H)
- log(O/H)

**Elemental Carbon**

- $^{13}\text{CO}$ (dex)

**Elemental Oxygen**

- $^{18}\text{O}$ (dex)

**New!**

- TBD!

**TBD!**
Next Steps: Test Correlation

Compare $^{12}\text{CO}$, $^{13}\text{CO}$, $^{18}\text{O}$ Abundances with:

- Stellar Age
- Metallicity (Fe/H)
- Elemental Carbon (C/H)
- Elemental Oxygen (O/H)

Coria+ in prep.
Next Steps: Test GCE Models

M-Dwarfs (Crossfield+ 2019):

Young Stellar Objects:

Kobayashi (2011) GCE Model:

Proposed GCE Correction:

Compare measurements to GCE models, find/explore any discrepancies

Determine causes for these inconsistencies!
Next Steps: Isotopic Analysis for Other Stars

1) Repeat abundance analysis for different stars: FGK(+M) binaries, moving group stars, field M-dwarfs, and JWST-targeted exoplanet host stars

2) Continue to test abundances for age correlation, GCE model discrepancies, etc…
Conclusion

• Isotopic Abundances are useful in the study of exoplanet atmospheres/composition AND in the calibration of GCE models.

• Stacked absorption lines allow for us to turn a set of relatively low S/N CO lines into a single CO profile with much higher S/N.

• Next Steps: Continue isotopic abundance analysis for different stars; test correlations and GCE models
Questions? Contact Me!

Thanks for listening!!! Any questions???

Email: drcoria@ku.edu