Is ozone (O_3) a reliable proxy for molecular oxygen (O_2)?

Thea Kozakis

João M. Mendonça, Lars A. Buchhave

Technical University of Denmark

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Why try to use O_3 as a proxy for O_2?

$\rightarrow$ O_2 + a reducing gas (i.e., CH_4) is a promising disequilibrium biosignature pair

There are scenarios where O_3 is more accessible than O_2

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No significant mid-IR O_2 features

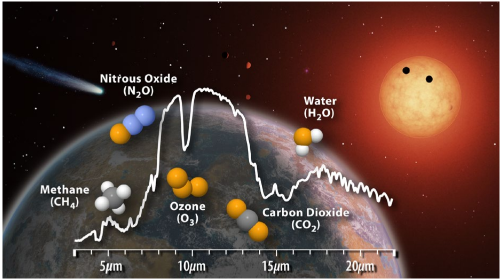

Figure from the Origins Final Report

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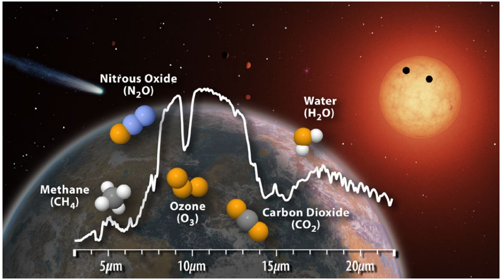

Figure from the Origins Final Report

O_3 is easier to detect at low O_2 levels

O_3 is created by photolysis of O_2 with a UV photon

Ozone formation:

$$
\begin{aligned}
O_2 + h\nu &\rightarrow O + O \ (\lambda < 242 \text{ nm}) \\
O + O_2 + M &\rightarrow O_3 + M
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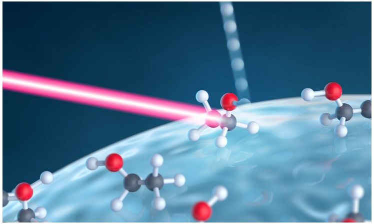

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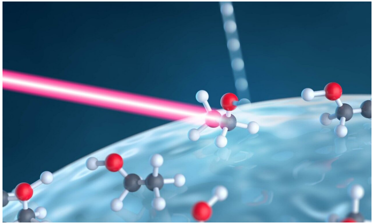

Important: O_3 production has a nonlinear relationship with O_2 and is extremely sensitive to changing stellar UV flux

Modeling Earth-like planets with varying O_2 to study the O_2-O_3 relationship

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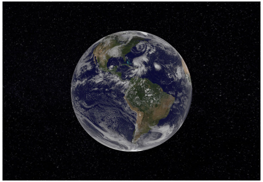
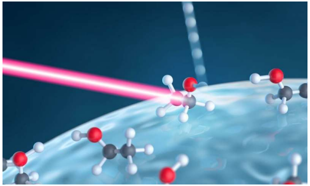
Climate code $\rightarrow$ $\leftarrow$ **Photochemistry code**





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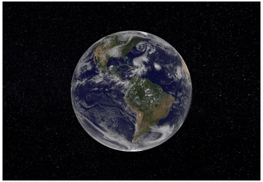

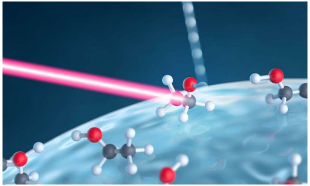

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Produces planetary emission spectra

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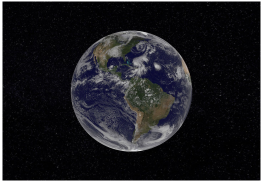

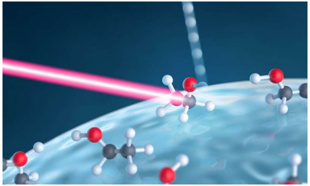

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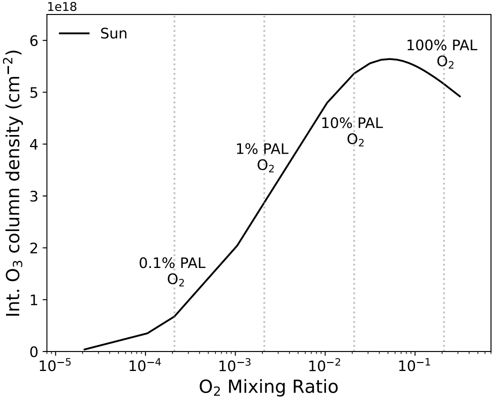
Varied O_2 levels from 0.01 - 150% PAL for Earth-like atmospheres
(PAL - Present Atmospheric Level)

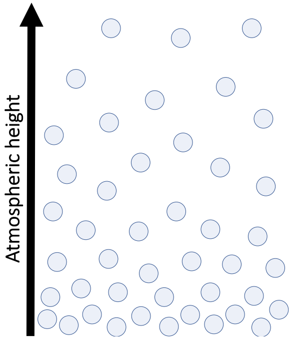
Peak O_3 abundance occurs at ~25% Earth's Present Atmospheric Level (PAL) of O_2

Earth-Sun sytem:

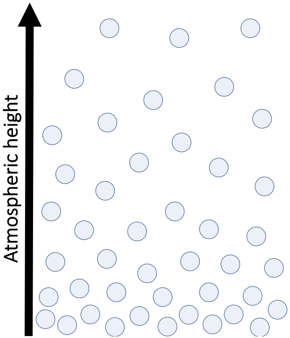


Less O_2 causes O_3 to form deeper in the atmosphere

100% PAL O_2



50% PAL O_2



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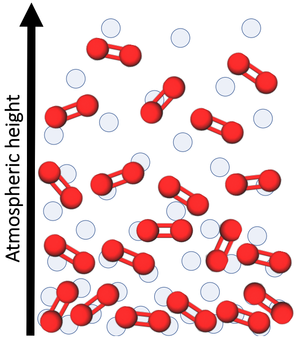

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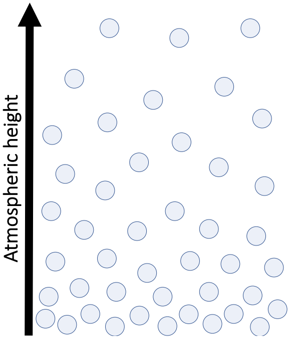

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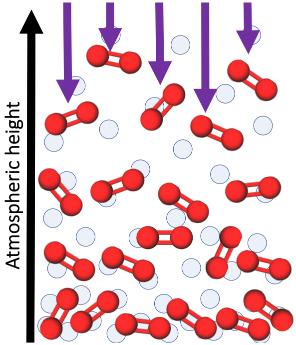

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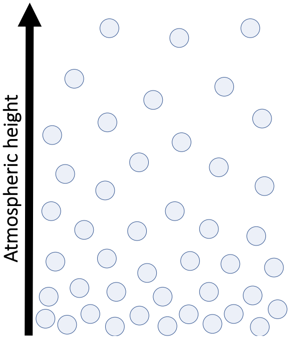

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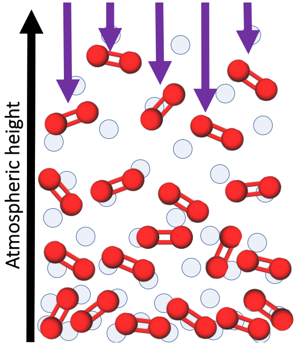

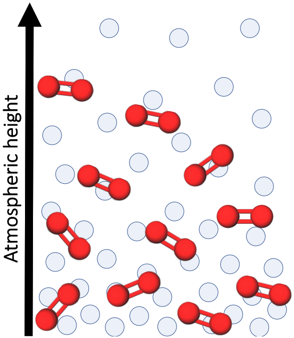

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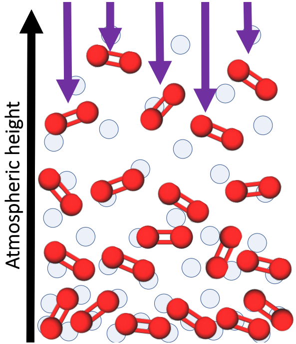

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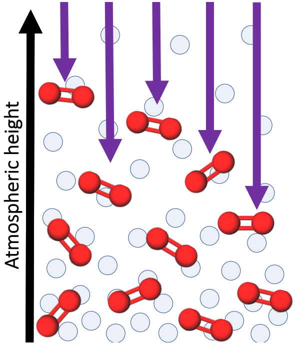
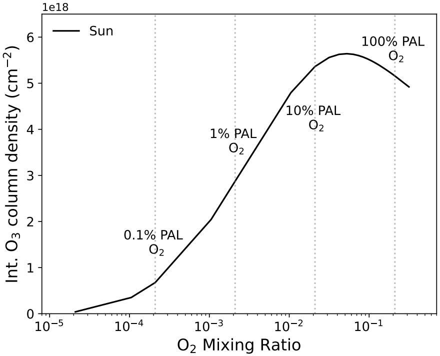


The 3-body reaction that forms O_3 is faster at higher densities

$$(O + O_2 + M \rightarrow O_3 + M)$$

Peak O_3 abundance occurs at $\sim$25% Earth's Present Atmospheric Level (PAL) of O_2

Earth-Sun system:



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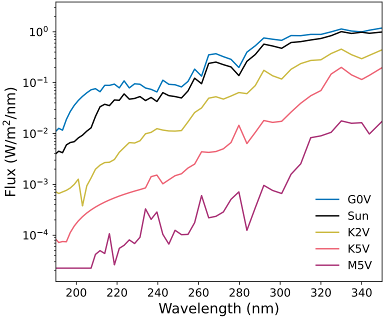
The O_2-O_3 relationship for different stellar hosts is dependent on the stellar UV spectrum



Stellar spectra are from Rugheimer et al. (2013) and MUSCLES

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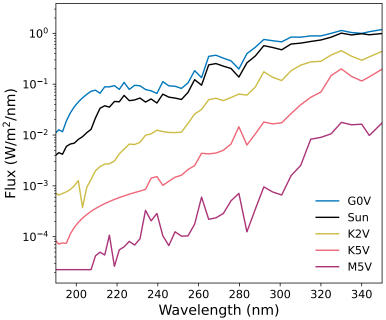

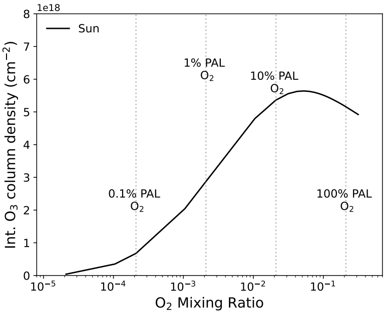

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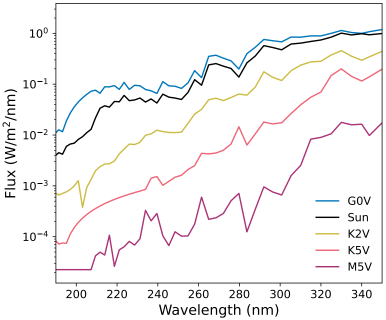

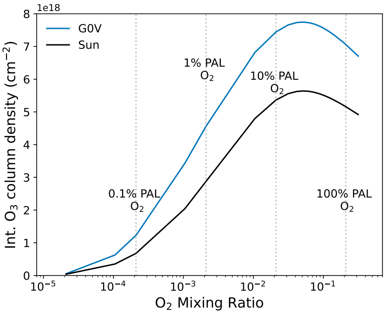

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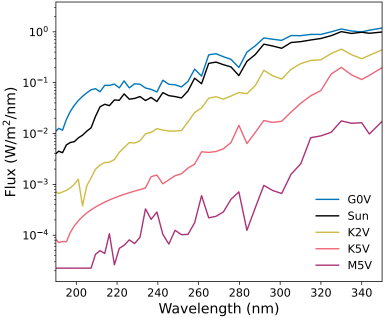

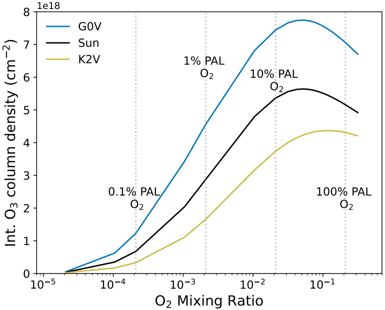

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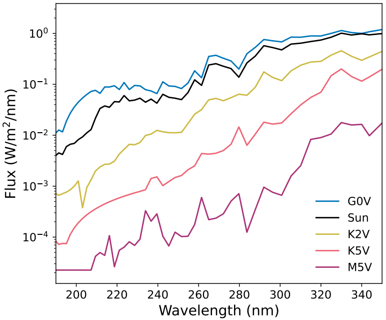

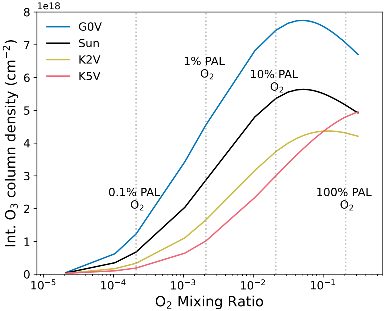

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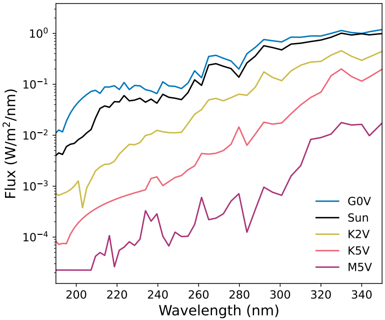

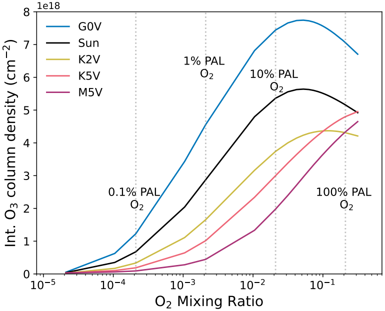

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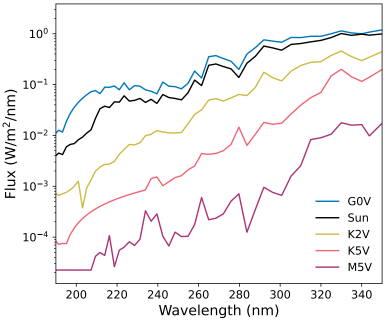

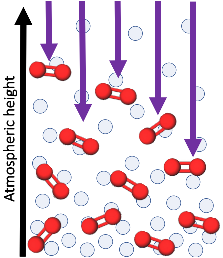

Cooler stars do not have enough photons capable of O_2 photolysis ($\lambda < 242$ nm) for O_3 abundance to increase when O_2 decreases

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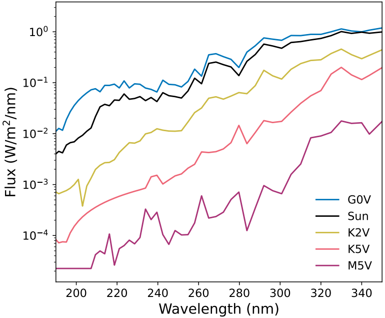

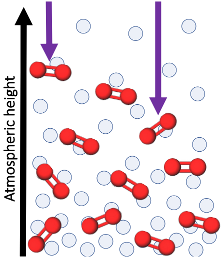

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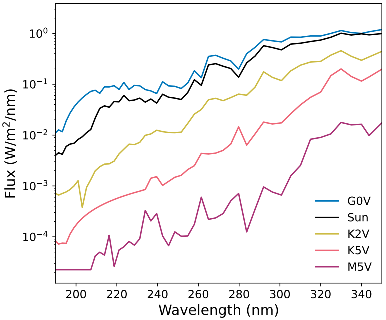

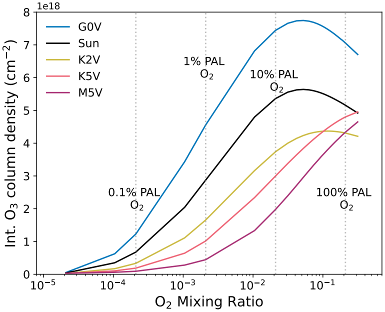

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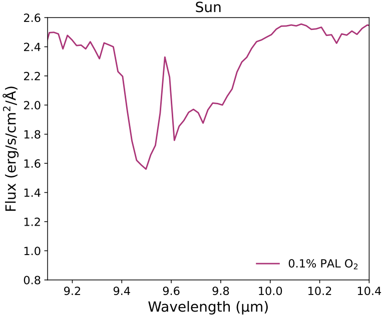
O_3 emission spectra features for hotter host stars are complicated

Ozone's 9.6 micron feature for Earth around the Sun:



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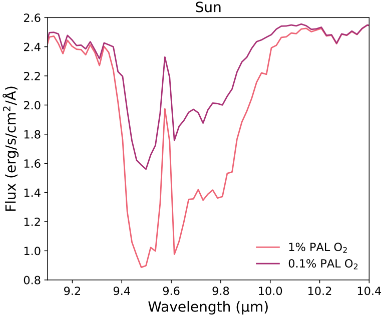

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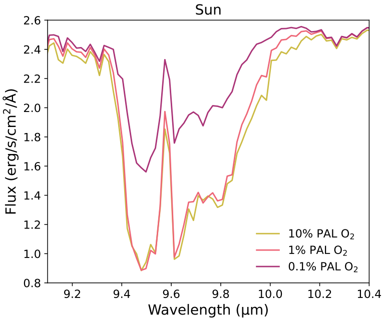

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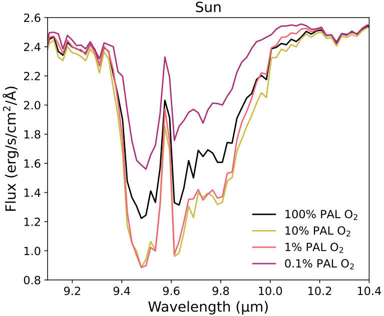

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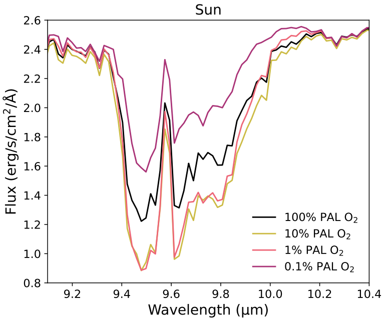

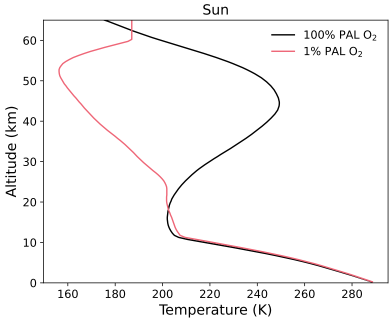

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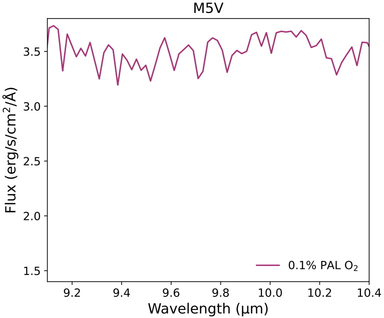
O_3 emission spectra features for cooler host stars are more straightforward

Ozone's 9.6 micron feature for Earth around an M dwarf:



Less stratospheric heating around stellar hosts with lower UV fluxes

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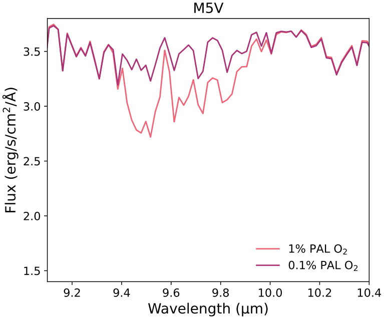

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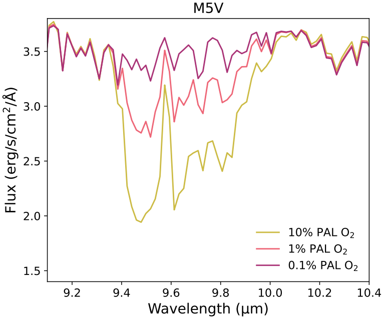

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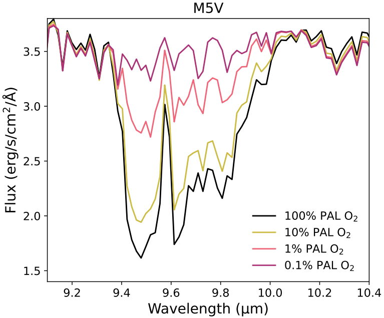

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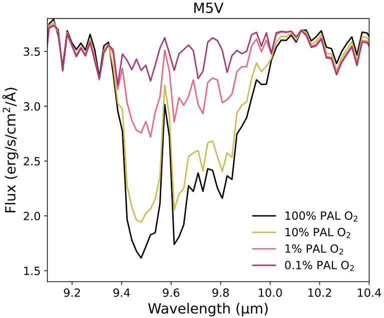
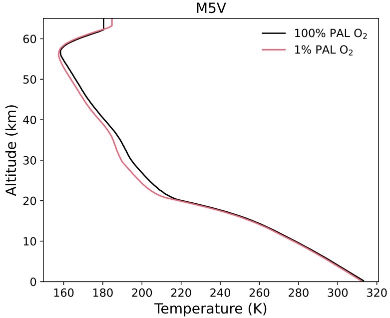
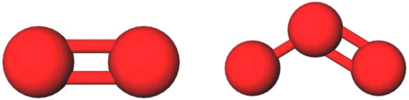




Less stratospheric heating around stellar hosts with lower UV fluxes

Is ozone (O_3) a reliable proxy for molecular oxygen (O_2)?

It's complicated, but we can understand it.



O_3 is more accessible than O_2 in biosignature searches:

- For mid-IR wavelengths
- For low O_2 levels

Need to:

- Understand the UV spectrum of host star
- Perform photochemistry/climate atmospheric modeling

You can read more in Kozakis et al. (2022) in A&A