Where is the Water?

Jupiter-like C/H ratio but strong \( H_2O \) depletion found on \( \tau \) Boötis b using SPIRou

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Where is the Water? Jupiter-like C/H but strong H$_2$O depletion found on $\tau$ Boo b.
Ahhh, Spirou, wake up! We’re going to be late to our class on giant planet formation!!

?!?!!!!!
A few moments later...

After hydrogen and helium, oxygen and carbon are the two most abundant elements in the universe.

Zzzzz

Ok, ok
Unfortunately, constraining both the O and C budget of giant planets can be very challenging, leaving us with many unanswered questions.

Öberg et al. 2011
You hear that Spirou? No time to waste, let’s get to work and try to find carbon and oxygen-based molecules on hot Jupiters!

I think I know just the instrument for this...
SPIRou Observations of $\tau$ Boo b

$\tau$ Boo b

1 - 2.5$\mu$m
R = 70,000
Thermal emission
5 nights/20 hours
But first, we have to clean-up the data!

Huh? So the planet signal is hidden somewhere in here??
Now with the data free of stellar and tellurics contamination, we can search for water on τ Boo b.

The Adventure Continues…
We use the SCARLET framework to generate atmospheric models of $\tau$ Boo b.

```
for i in range(1000000):
    print('Atmospheres, Atmospheres! Do I look...')
```
Huh?? No water at the known planet location?!? That's unexpected!
But wait, look! There seems to be CO absorption! CO but not H$_2$O on τ Boo b??? I expected the opposite!
Well?? What do you make of the CO?

CO line shape --> TP profile

Retrieved non-inverted TP Profile
Why stop at only H$_2$O and CO?

What about other Molecules?
CO ~5 times solar

H$_2$O <0.007 times solar

No other molecules

Relatively cloud-free

Full Retrieval Results

| Parameter                  | Value                  |
|----------------------------|------------------------|
| VMR log(CO)                | $-2.46^{+0.25}_{-0.29}$|
| VMR log(H$_2$O)            | $<-5.66$ (3$\sigma$ upper limit) |
| VMR log(CH$_4$)            | $<-3.78$ (3$\sigma$ upper limit) |
| VMR log(CO$_2$)            | $<-3.99$ (3$\sigma$ upper limit) |
| VMR log(HCN)               | $<-5.37$ (3$\sigma$ upper limit) |
| VMR log(TiO)               | $<-7.54$ (3$\sigma$ upper limit) |
| VMR log(C$_2$H$_2$)        | $<-4.88$ (3$\sigma$ upper limit) |
| VMR log(NH$_3$)            | $<-6.10$ (3$\sigma$ upper limit) |
| Cloud-Top Pressure ($P_c$) | $>0.26$ bar (3$\sigma$ lower limit) |
| Scaling Parameter ($a$)    | $1.04 \pm 0.03$        |
| Keplerian Velocity ($K_p$) | $109.2 \pm 0.4$ km s$^{-1}$ |
| Systemic Velocity ($V_{sys}$) | $-15.4 \pm 0.2$ km s$^{-1}$ |
\( \tau \) Boo b's C/H ratio is \(~3-10\) times solar and consistent with the value of Jupiter.
Similarly, we find an O/H ratio 2-12 times solar, consistent with the recent JUNO results for Jupiter.
HD 189733b, HD 209458b, and τ Boo b all seem to follow a trend of elevated CO and depleted H$_2$O abundances. This may hint towards elevated C/O ratios being common on hot Jupiters.
The combination of a super-solar C/O ratio AND a super-solar metallicity most likely indicates a formation scenario further out in the disk, possibly due to pebble drift, followed by disk-free migration.
Summary

- Super-solar abundance of CO found on τ Boo b using SPIRou

- Depletion of H$_2$O, the consequence of a super-solar C/O ratio (NOT a low metallicity)

- Favored formation mechanism: gas accretion beyond the iceline + disk-free migration