Water Detected in the Terrestrial Zone of Exoplanetary Systems

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The Story of Water on Earth in Three Images

Total Earth H₂O tiny yet critical!



Earth-like surface water not detectable by known methods

Asteroids: Terrestrial + Impactors

Leftover building blocks of the terrestrial planets meteorites provide inner Solar System compositions



Jupiter perturbs asteroids

Possibly delivered H_2O + volatiles to Earth

D/H ratios match the oceans large mass for each impact



Ceres is 25% $\rm H_2O$ by mass

Destabilized Asteroids near the Snow Line



Exo-Asteroid Belts near the Snow Line

- Four exoplanetary systems with 2 belts each
 - outer disks are Kuiper belt analogs $T \approx 50$ K
 - inner disks are main belt analogs $T \approx 170 \text{ K}$
- All four require planets to separate the two belts – these may be Jupiter + main belt analogs
 - planets can then perturb snow-line asteroids
- Represent architectures similar to the Solar System
- Polluted white dwarfs have similar architecture – descendants of stars like Fomalhaut, Vega, HR 8799



Atmospheric Pollution by Disrupted Asteroids

Asteroid chemistry observed in star



Tidally disrupted asteroid / (a la Saturn's Rings)



Disk emits in infrared







Polluted Stars Tell a Terrestrial Story

- Abundances broadly mimic the bulk Earth
 - dominated by Mg and Fe silicates
 - more C-depleted than primitive meteorites
- Evidence for differentiated parent bodies
 - indicates melting, collisions (e.g. Moon)
 - large planetary leftovers or fragments
- $10^{22} \text{ g} < M_{\text{accreted}} \sim 10^{25} \text{ g}$ (Pluto)



A Snow-Line Exo-Asteroid

- Rocks composed of metal oxides: MgO, Al₂O₃, SiO₂, CaO, FeO
 – excess oxygen in debris can indicate H₂O
- Excess 0 in the debris at GD 61

 HST, FUSE, Keck I + II
 CO/CO₂ ruled out by O/C > 1000
- 26% H₂O by mass - similar to Ceres
- Asteroid mass similar to Vesta – using trace H



Artist's depiction of H₂O-rich asteroid at GD 61

H₂O + Differentiation in GD 61 Debris

Normalised Flux Excess Fe0 0.5 CaO Oxygen Fraction in Metal Si0, 0.6 0 1250 1255 1260 1265 Al_O Mg0 0.4 Normalised Flux 0.2 0.5 0.0 EP SS Eart Moon Vesta Mars 0 1305 1310 1295 1300 1334 1335 1336 Wavelength [Å] iron deficit



possible fragment of water-rich planet exterior

oxygen excess

A Second Water-Rich Exo-Asteroid

oxygen excess Ti II 60% 1.4 10% 25% 40% Ti I 0% 30% 50% 70% 80% 90% 100% Fe I Fe II 1.2 Call He I He I He I CaI He Normalised Flux 0.6 0.4 0.4 0.2 Mg I Si II ահաստու 37 3200 3400 3600 3800 4000 4200 4400 Wavelength [Å] 1.2 He Si II ΟI steady state 1.1 Π 1.0 Normalised Flux 8.0 8.0 8.0 Feothers Me 0 et cess SiOr 0.6 Na Mg II 0.5 0.4 L 6400 6600 6800 7000 7200 8000 7800 8200 8400 8600 8800 6000 6200 Wavelength [Å] Wavelength [Å]

Raddi et al. 2015, MNRAS

38% H₂0 by mass

Traces of H₂O via H in He Atmospheres



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Summary

- 1. Snow lines are important in the Solar and extrasolar planetary systems H₂O and volatile delivery may occur via main belt analogs
- 2. HR 8799, Vega, Fomalhaut may have Jupiter + main belt analogs polluted white dwarfs appear to share this architecture!
- 3. Evidence for H₂O-rich asteroids in at least 2 exoplanetary systems extant tools: planets to perturb bodies towards star extant ingredients: rocky yet water-rich asteroids



