Electron Beam Simulations in Substellar Atmospheres

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What are the observational consequences of auroral processes in substellar atmospheres?

Motivation + Background

Brown dwarfs offer a unique **proxy for studying exoplanet atmospheres**:
- Similar atmospheric temperatures despite higher mass
- Magnetic behavior more similar to exoplanets than stars [10]
- **Observationally accessible** analog for exoplanet atmospheric physics

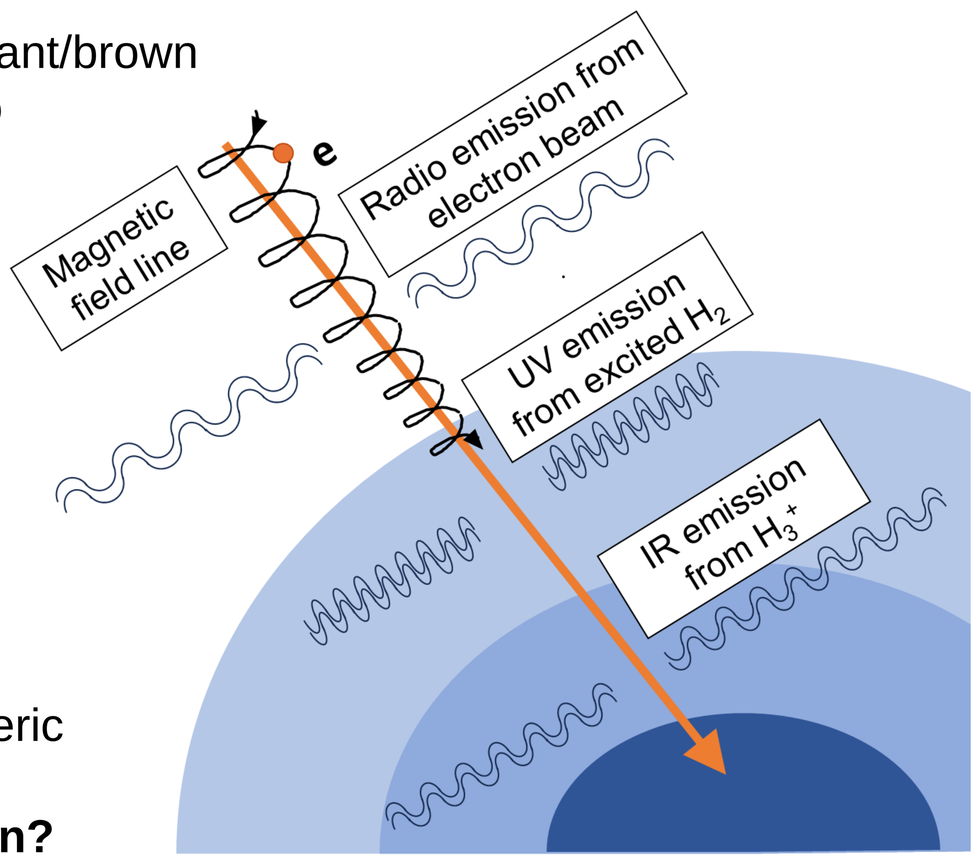
Goal: Understand brown dwarf auroral processes as a proxy for exoplanets

In the **solar system** (i.e., Jupiter):
- Electron beams interact with planetary atmospheres to produce aurorae
- Visible in the radio, UV, and IR [10]
- Electron beams produced via magnetospheric dynamics or satellite interactions. Mechanisms include:
  1. Interaction of solar wind and magnetosphere
  2. Interaction of orbiting satellites and magnetosphere
  3. Co-rotation breakdown of plasma

Beam **mechanism and energy** are likely to **affect observable emission**

Current theory for substellar (gas giant/brown dwarf) aurorae **relies on scaled-up Jovian model**
- But **observations suggest different physics** is at play
- **Radio** aurorae observed in brown dwarfs [2]
- No corresponding detection in the **UV or IR** [10]
- Implies physics is different from Jovian case
- Observing IR emission from H_3^+ would be diagnostic of atmospheric properties

What explains this non-detection?

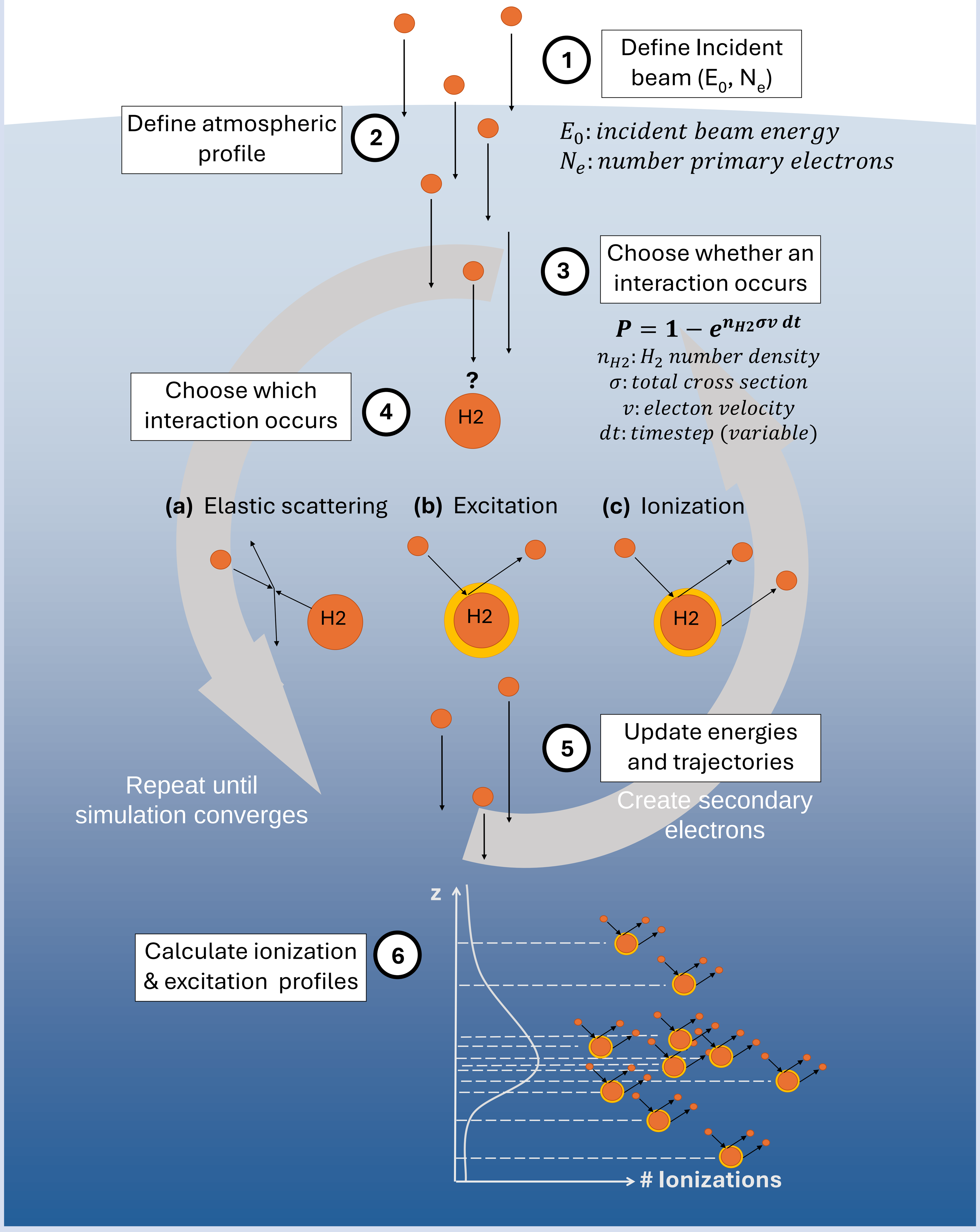


Pineda et al. (2024) suggest UV and IR non-detection is due **to higher energy electron beams**
- More energetic beams produce ionizations **deeper in the atmosphere**
  - **Ionized H_3^+ is destroyed** by chemistry before it can emit in the IR
- Excitation also happens deeper for more energetic beams
  - UV from excited H_2 **undergoes greater extinction** due to thicker overlying material
- Radio emission from electron beam (produced by strong magnetospheric current system) itself still observed

Goal: understand non-detections by modeling substellar atmospheric physics
- What **auroral signatures should we expect to observe** from electron beam interactions in brown dwarf atmospheres?
- What atmospheric and beam properties are most **consistent with observed radio aurorae**?

Model Schematic

We run a Monte Carlo kinetic simulation modeling the **interactions of energetic electrons** as they propagate through a substellar atmosphere:



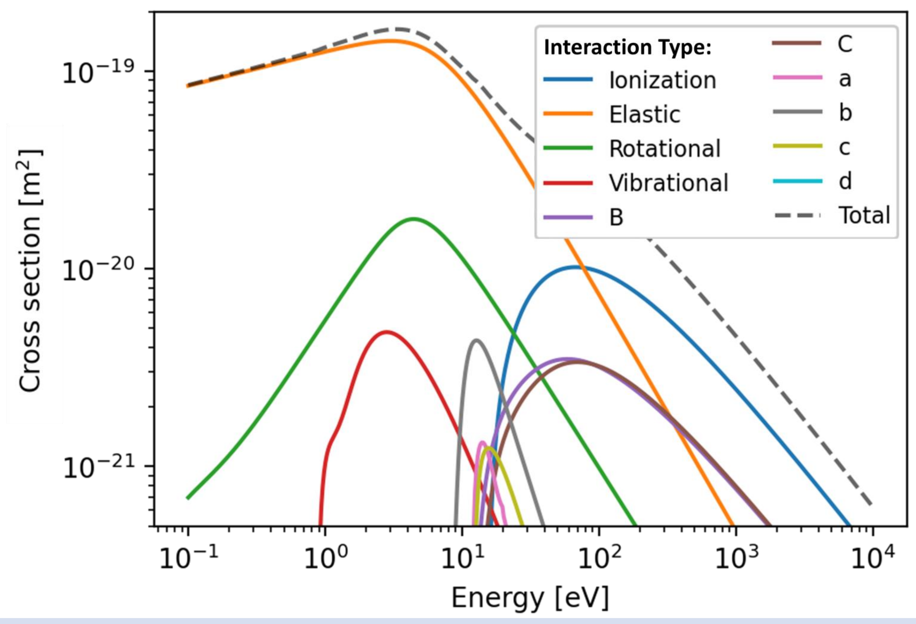
Model Parameters

Density profile: H_2 atmosphere, profiles from custom Sonora models [5, 6, 8]

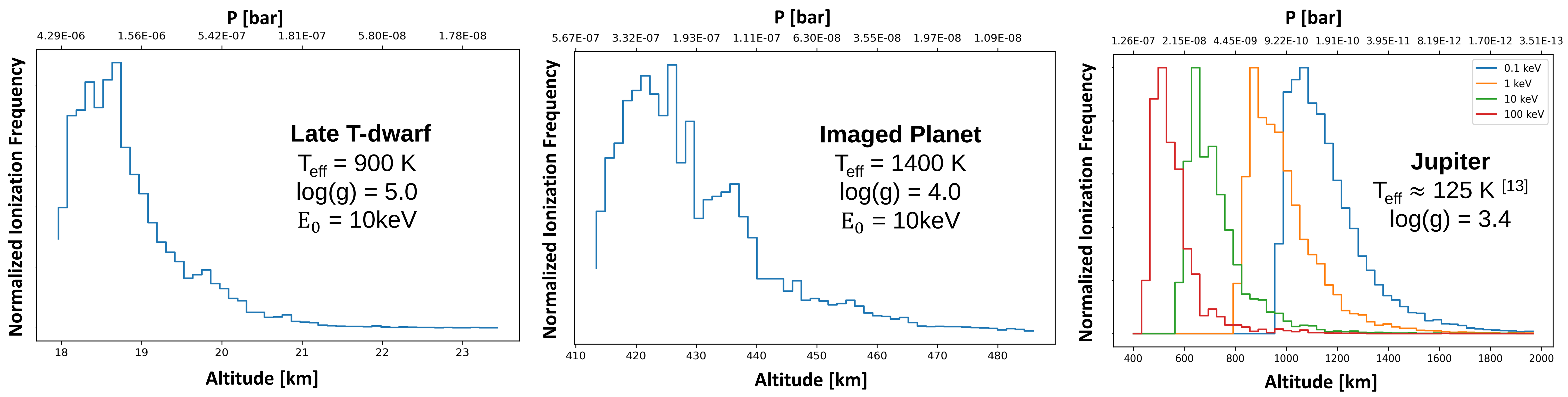
Cross sections: Cross sections taken from NIST [4] and MCCC database [6]

Energy partition: Taken from Vahedi (1995) and MCCC database [6]

Scattering angle: Screened Rutherford for ionization and elastic scattering, isotropic for others



Initial Results



Key results:
- Ionization rate peaks at very **different pressure levels** for each atmospheric profile
- Peaks **deeper in the atmosphere** with increasing beam energy
- Width due to cascade of **secondary electrons**

Future work priorities include:
- Treatment of **atmospheric chemistry** for energy deposition profile: can we explain JWST observations of brown dwarf thermal inversion?
- Further **optimization** of algorithm for efficiency
- Implementation of **non-uniform beam energy distribution**
- **Parametrization** of ionization rate with altitude and energy

References: [1] Gibbs & Fitzgerald 2022, [2] Hallinan et al. 2015, [3] Hiraki & Tao 2008, [4] Kim et al. 2004, [5] Marley et al. 2021, [6] MCCC Database, [7] Morley et al. 2024, [8] Mukherjee et al. 2024, [9] Pineda et al. 2017, [10] Pineda et al. 2024, [11] Saur et al. 2018[12], Vahedi & Surendra 1995, [13] Vazan et al. 2017

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