Red Dwarf Upside-Down Cake

M Dwarf Evolution from a Brown Dwarf Perspective

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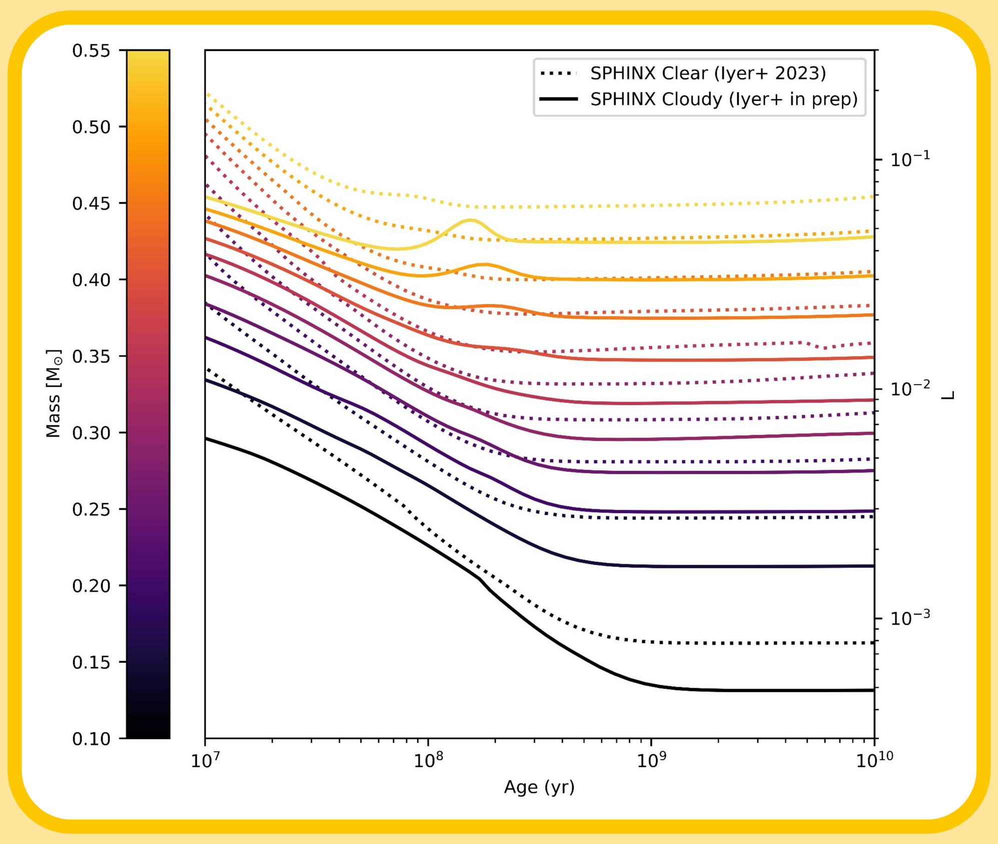
Introduction

M dwarfs make up 75% of all dwarf stars in the solar neighborhood, host a myriad of exoplanets, and push up against the hydrogen-burning minimum mass (HBMM), making them of great interest to all kinds of astronomers. However, discrepancies between stellar evolution models and observations of M dwarfs have existed for decades, suggesting major issues in our understanding of these stars. Current models have difficulty reproducing Gaia M dwarf color-magnitude diagrams, underestimate M dwarf radii by 5~10%, and overestimate their luminosities by the same margin. This affects exoplanet radii, density, and bulk composition. These discrepancies may stem from approaching M dwarf evolution from "the top down," i.e., using the same physics and assumptions as in higher mass stellar models. M dwarf atmospheric opacities are dominated by molecules — in contrast to the atomic opacity dominated atmospheres of Sun-like stars. Additionally, M dwarf interiors are partially degenerate, unlike the ideal gas interiors of Sun-like stars. **Modeling M dwarfs with tools built for higher mass stars ignores critical physical differences, resulting in inaccurate properties of exoplanets and fundamental properties of these abundant, exoplanet-hosting stars.**

The recently published **SPHINX M-dwarf Spectral Grid (Iyer et al. 2023)** adapted an atmosphere model originally designed for the molecule dominated environments of brown dwarfs and giant planets. Additionally, after 30 years, the interior "Equation of State" was recently updated by Chabrier et al. (CDMS), making significant improvements in the ρ-T regime that brown dwarfs and low mass M dwarfs occupy. **We integrate state-of-the-art atmospheres and a new equation of state into two widely-used stellar evolution codes to close gaps between models and observations of M dwarf stars.**

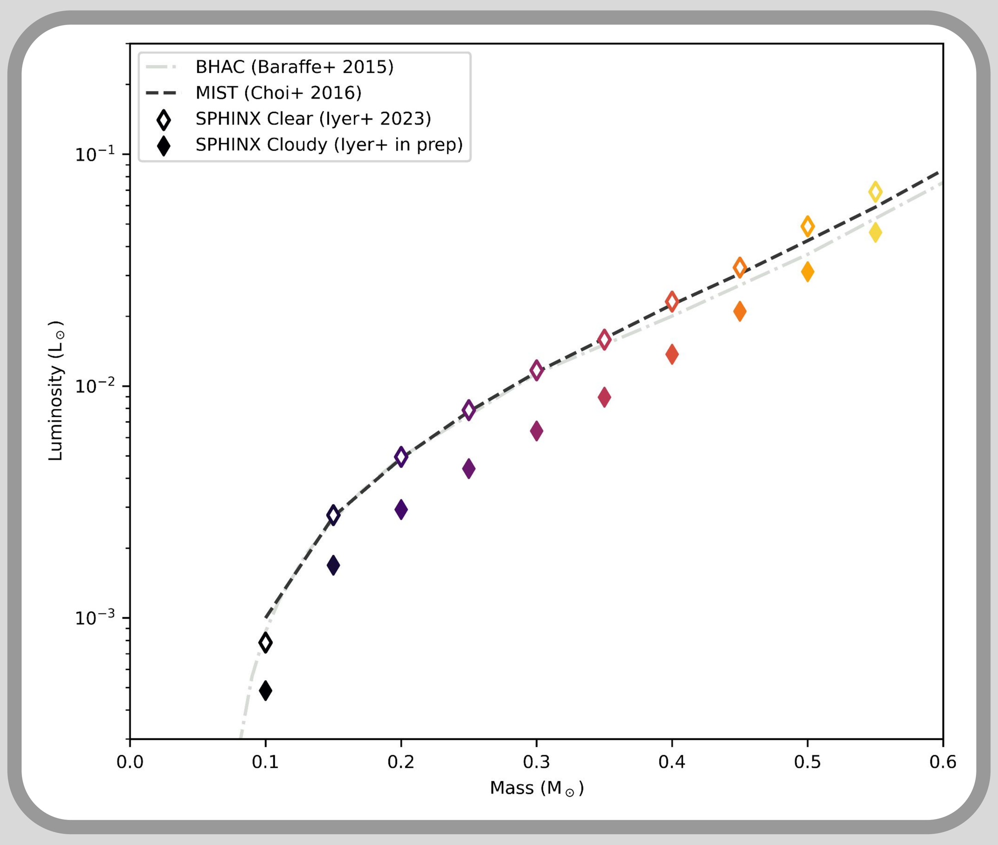
Results: MESA + SPHINX

Luminosity vs. Time



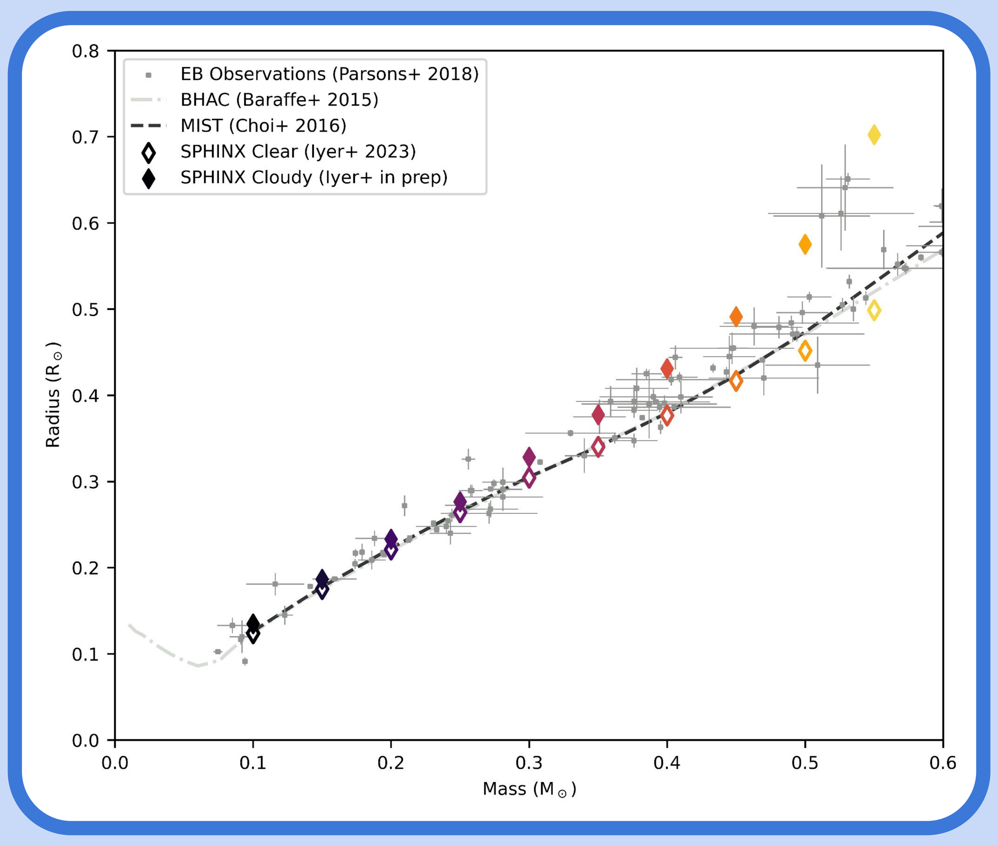
The luminosities of our "cloudy" cases (solid lines) are consistently dimmer than our "clear" cases (dotted lines), especially in the pre-main sequence (PMS) phases of our stars. The "cloudy" cases are also older when they enter the main sequence (ZAMS) than their "clear" counterparts. Cloudy atmospheres make it more difficult for gravitational energy to be radiated away from the star as it contracts, resulting in a longer Kelvin-Helmholtz timescales and a higher ZAMS. **Atmospheric clouds/dust results in M dwarfs that contract slower and are dimmer during their PMS phases.**

Mass vs. Luminosity @ 10 Gyr



At an age of 10 Gyr, our "clear" cases (hollow diamonds) are, on average, 102% as luminous as those from MIST. In contrast, our "cloudy" cases (filled diamonds) are, on average, only 62% as luminous as MIST. Both cloudy and clear 0.1 $M_\odot$ cases show much lower luminosities than MIST, but exhibit similar behavior as described above when compared to BHAC. **Including atmospheric clouds/dust results in significantly lower luminosities for stars with masses of 0.1-0.55 $M_\odot$.**

Mass vs. Radius @ 10 Gyr



At an age of 10 Gyr and below 0.3 $M_\odot$, our cloudy cases (filled diamonds) and clear cases (hollow diamonds) match well with previous theoretical studies (dashed and dotted lines) and measurements from eclipsing binary systems (grey points). Above 0.3 $M_\odot$, our clear cases have smaller radii than BHAC and MIST, while our cloudy cases enhance stellar radii by ~10-50% compared to these previous studies. **Modeling atmospheric clouds/dust results in larger radii, with potential to close the M dwarf M-R gap.**

Take-Away

A simple treatment of cloud opacities in the atmospheres of M dwarfs results in larger radii and lower luminosities for all stellar evolution simulations.

Our work showcases the need for more robust cloud modeling, and the potential for clouds to reconcile (at least part of) the differences between theory and observations of M dwarfs.

Methods

- **SPHINX:**
  The SPHINX atmospheres are gridded in $\log_{10}g$ (4.0 – 5.5, Δ0.25), T_{eff} (2000 – 4000K, Δ100K), $\log_{10}\kappa_{cloud}$ (-32 – -28, Δ1), $\log_{10}Z/Z_\odot$ (-1 – 1, Δ0.25), and C/O (0.3 – 0.9, Δ0.2). Pressure-temperature profiles from SPHINX are used to create tables of T_{10} (temperature at 10 bar) across a $\log_{10}g$-T_{eff} grid, which form the upper boundary condition of MESA's interior profile. Note that SPHINX's "clouds" are grey (λ-independent) and simply added to the net opacity, maximizing the atmospheric warming effect. Thus, our "cloudy" ($\log_{10}\kappa_{cloud}$=-28) cases act as a "0^{th} order" upper limit of how clouds can influence stellar evolution.
- **MESA:**
  MESA is flexible and extendable, capable of modeling masses from gas giants to super-massive stars. This Henyey code iteratively solves the structure equations in "mass shell" space, and determines whether a given mass shell is convective or radiative. MESA can not (yet) use CDMS, though work is nearly complete on an integration. We therefore opt to use a second stellar evolution model, Sonora (Marley et al. 2021), with CDMS.
- **Sonora:**
  Sonora is light and nimble, and has been used extensively to model the interiors of brown dwarfs and giant planets. Unlike MESA, Sonora assumes purely adiabatic convection throughout the interior. Because we are primarily interested in using CDMS to update constraints on the HBMM, our Sonora simulations will be at low masses (M<0.2 $M_\odot$) where M dwarfs are fully convective. This makes Sonora an appropriate model for our use case.
- **Evolution Tracks:**
  We run two grids of stellar evolution simulations, the first using MESA (0.1 - 0.55 $M_\odot$, Δ0.05 $M_\odot$) and the second with Sonora (0.05 - 0.2 $M_\odot$, Δ0.01 $M_\odot$) to 10 Gyr.