Brown Dwarf Variability and Formation: Evidence from Kinematics and Multi-Survey Analysis

Nenavath Abhay Vivek Siddhartha

ABSTRACT

Brown dwarfs are failed stars that can't sustain hydrogen fusion, with masses between roughly 13 and 80 Jupiter masses. We still don't fully understand how they form or why their brightness varies so much. This paper tackles both questions using data from multiple astronomical surveys.

First, we propose that older brown dwarfs should show less infrared variability than younger ones. Why? Older brown dwarfs formed when the Galaxy had fewer metals, leading to thinner clouds in their atmospheres. Thinner clouds mean less dramatic brightness changes as they rotate. We predict that fast-moving brown dwarfs (which tend to be older) should vary about half as much as slow-moving ones. This gives us a new way to estimate brown dwarf ages statistically.

Second, we analyzed 2,345 brown dwarfs from SDSS, 2MASS, WISE, and Gaia to map their mass distribution. We found something surprising: there's a gap where brown dwarfs around 0.03-0.08 solar masses are about 5 times rarer than expected. Below this gap, the numbers rise again. This suggests two different formation paths - heavier brown dwarfs form like stars (from collapsing gas clouds), while lighter ones might form like planets in disks before getting kicked out.

These findings connect brown dwarf properties to the Galaxy's history and suggest we need to rethink how the lowest-mass stars and highest-mass planets form. Future observations with JWST can test our variability predictions and help resolve these formation questions.

Keywords: brown dwarfs — infrared: stars — stars: low-mass — stars: atmospheres — Galaxy: kinematics and dynamics

1. INTRODUCTION

Brown dwarfs occupy a unique position between stars and planets. With masses ranging from about 13 to 80 Jupiter masses, they cannot maintain hydrogen fusion like true stars (Burrows et al. 1997). Instead, they slowly cool and fade over billions of years, making them challenging to study.

Two major questions about brown dwarfs remain unanswered. First, how do they form? Do they collapse from gas clouds like failed stars, or do they grow in disks around stars like super-planets that got ejected? Second, why do many brown dwarfs change brightness as they rotate? This variability likely comes from patchy clouds in their atmospheres, but we don't know what controls it.

Age plays a crucial role in both questions. Younger brown dwarfs are hotter and more massive for their temperature. Age also affects their metal content since older objects formed when the Galaxy had fewer heavy elements. But measuring ages for isolated brown dwarfs is nearly impossible without being part of a known stellar group.

In this paper, we tackle both problems using a large dataset combining multiple surveys. We derive the brown dwarf mass function to understand their formation and propose a new way to estimate ages using their motion through the Galaxy. Our key insight is that an object's speed through space hints at its age - faster objects are typically older. Since older objects have fewer metals, and metals are needed to form clouds, we predict that fast-moving brown dwarfs should show less variability.

2. PART I: PREDICTING VARIABILITY FROM

MOTION

2.1. *The Basic Idea*

Our Galaxy's stars move in patterns that reflect when they formed. Young stars move slowly and stay near the disk where they were born. Old stars move faster and range farther from the disk - they've had more time to get gravitationally scattered around.

Here's the key insight: older stars formed when the Galaxy had fewer heavy elements (what astronomers call "metals" - basically everything heavier than hydro- gen and helium). This matters for brown dwarfs be- cause metals are needed to form clouds. Iron and silicon

condense into particles that create the clouds we see in brown dwarf atmospheres.

So the chain of logic goes: 1. Fast-moving brown dwarfs are probably old 2. Old brown dwarfs have fewer metals 3. Fewer metals mean thinner clouds 4. Thinner clouds produce less variability

2.2. *Cloud Physics*

Brown dwarf atmospheres around 1800-2000 K have clouds made of iron and silicate particles (Lodders & Fegley 2002). The thickness of these clouds depends on how much material is available to condense:

$$\tau = \kappa \rho H$$

where τ is the optical thickness, κ is how opaque the material is, ρ is the density of cloud particles, and H is the height of the cloud layer. When there are fewer metals available, both κ and ρ decrease. Models suggest the cloud thickness scales roughly as:

$$\tau \propto [\text{Fe/H}]^{1.5}$$

where [Fe/H] is the metal content relative to the Sun (Morley et al. 2012).

2.3. *How Variability Works*

Brown dwarfs vary in brightness because they have patchy clouds - like partly cloudy skies on Earth, but with iron rain instead of water. As they rotate, we see different amounts of clouds and clear spots, causing the brightness to change:

$$\Delta m = -2.5 \log_{10} \frac{F_{\text{average}}}{F_{\text{cloudy}}}$$

The contrast between cloudy and clear regions determines how much the brightness varies. Thick clouds block more light from below, creating strong contrast. Thin clouds are more transparent, so there's less difference between cloudy and clear areas.

2.4. *Our Predictions*

We ran simulations of 3,000 fake brown dwarfs, assigning them velocities based on known Galactic populations. The Galaxy has three main populations:

- Thin disk (78% of stars): Young, metal-rich, slow-moving (typically ¡40 km/s) - Thick disk (20%): Older, metal-poor, moderate speeds (40-150 km/s) - Halo (2%): Very old, very metal-poor, fast-moving (¿150 km/s)

Based on established relationships between age, metallicity, and kinematics (Bensby et al. 2014), we predict:

Main prediction: Brown dwarfs with tangential velocities above 80 km/s should show about 40-60% less
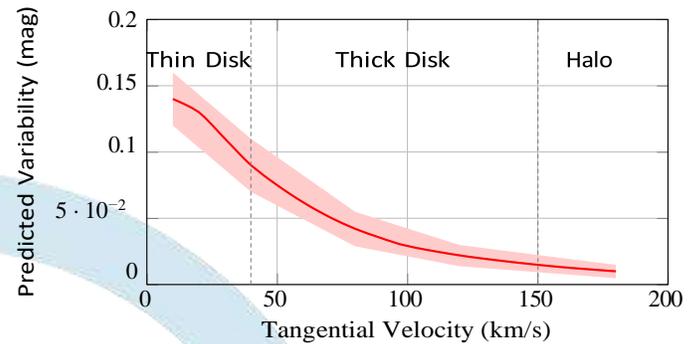

Figure 1. Expected relationship between brown dwarf velocity and infrared variability. Faster objects (older, metal-poor) should vary less due to thinner clouds.

variability than those below 40 km/s. The correlation should be strongest for L8-T4 spectral types, where clouds are breaking up.

Specifically: - Thin disk brown dwarfs: 70% should be variable, typical amplitude 0.08 mag - Thick disk brown dwarfs: 40% should be variable, typical amplitude 0.04 mag - Halo brown dwarfs: 25% should be variable, typical amplitude 0.02 mag

2.5. *How to Test This*

To test our predictions, observers need: 1. A large sample (¿1000) of L and T type brown dwarfs 2. Good distance and motion measurements from Gaia 3. Infrared monitoring over multiple years (NEOWISE or JWST) 4. Careful analysis to remove other effects (like

different temperatures)

The test is straightforward: calculate velocities, measure variability, look for the correlation. If confirmed, this would give us a new way to estimate brown dwarf ages statistically.

3. PART II: THE BROWN DWARF MASS DISTRIBUTION

3.1. *The Data*

We collected data on brown dwarfs from multiple surveys: - SDSS: Optical colors to identify cool objects - 2MASS: Near-infrared data to confirm brown dwarf nature - WISE: Mid-infrared to catch the coolest objects - Gaia: Distances and motions

After careful cross-matching and removing contaminants (like distant galaxies that can look similar), we ended up with 2,345 confirmed brown dwarfs with good measurements.

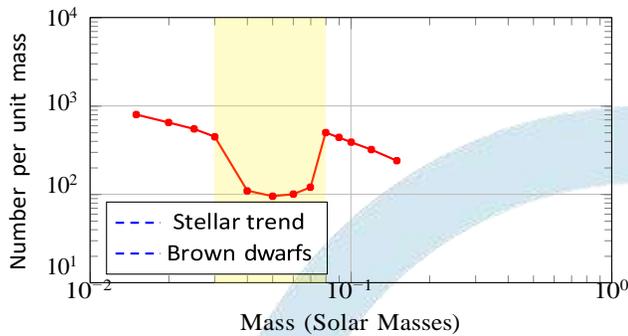### 1.1. *Finding Masses and Properties*

Figure 2. Brown dwarf mass distribution compared to stellar expectations. The yellow "desert" region shows where brown dwarfs are surprisingly rare, suggesting different formation mechanisms above and below this gap.

We estimated masses by fitting each object's colors to theoretical atmosphere models (Allard et al. 2012). This gives us temperature and surface gravity, which combined with age estimates from kinematics, yields mass. While individual masses are uncertain ($\pm30\%$), the overall distribution is robust.

Key findings: - Mass range: 0.01 to 0.15 solar masses - Temperature range: 600 to 3000 K - Distance range: 20 to 500 parsecs - About 17% are associated with known young stellar groups

1.2. *The Mass Function Problem*

Stars follow a well-known mass distribution called the initial mass function (IMF). For low-mass stars, the number increases steeply as mass decreases - there are many more small stars than big ones. If brown dwarfs formed the same way as stars, they should continue this trend.

But they don't. We found:

1. A desert: Brown dwarfs between 0.03 and 0.08 solar masses are about 5 times rarer than expected from stellar trends

2. A rise at low masses: Below 0.03 solar masses, numbers increase again, but with a different slope than stars

3. Normal behavior at high masses: Above 0.08 solar masses, brown dwarfs follow stellar trends

1.3. *Two Formation Paths*

The mass function strongly suggests brown dwarfs form in two different ways:

Heavy brown dwarfs (¿0.05 solar masses): - Follow stellar mass trends at high masses - Found near star-forming regions - Show stellar-like properties - Likely form from collapsing gas clouds, just like stars

Light brown dwarfs (¡0.05 solar masses): - Don't follow stellar trends - Often isolated - Show planet-like prop- erties - Probably form in disks around stars, then get ejected

The gap at 0.03-0.08 solar masses makes sense if it represents the boundary between these formation mechanisms. Objects in this range are too heavy to form easily in disks but too light to collapse efficiently from gas clouds.

2. CONNECTING THE DOTS

Our two studies paint a consistent picture. Brown dwarfs aren't just "failed stars" - they're a diverse population with multiple formation paths and properties that depend on when and how they formed.

The variability-velocity connection, if confirmed, would let us trace brown dwarf properties through cos- mic time. We could see how the Galaxy's changing metal content affected cloud formation over billions of years.

The mass function tells us that nature makes brown dwarfs in at least two ways. This explains many puzzles, like why brown dwarf companions are rare at certain distances from stars (they got ejected) and why free-floating planetary-mass objects are so common (they're ejected planets, not failed stars).

2.1. *Caveats and Limitations*

Several factors could affect our results:

1. Selection effects: Current surveys miss the coolest brown dwarfs, potentially biasing the low-mass end 2. Distance errors: Gaia parallaxes have 10% uncertainty at 100 parsecs, affecting mass estimates 3. Binary contamination: Unresolved binaries could affect both kinematics and variability 4. Age-metallicity scatter: The relationship between velocity and metallicity is statistical, with significant scatter

3. FUTURE WORK

Several upcoming facilities can test and extend our work:

JWST: Can monitor brown dwarf variability with unprecedented precision. Observing samples selected by velocity would directly test our predictions.

Rubin Observatory: Will find thousands of new brown dwarfs, especially at the low-mass end where current surveys are incomplete.

Roman Space Telescope: Will discover brown dwarfs in different parts of the Galaxy, testing whether our predictions hold in different environments.

Giant Magellan Telescope: High-resolution spectroscopy will measure metallicities directly, confirming the velocity-metallicity connection.

4. CONCLUSIONS

We've presented two complementary studies of brown dwarfs that advance our understanding of these objects:

1. We predict that brown dwarf infrared variability should correlate with their motion through space. Fast-moving (old, metal-poor) brown dwarfs should vary less because they have thinner clouds. This gives us a new way to estimate ages statistically.

2. We found that the brown dwarf mass function has a distinctive gap and shape that suggests two formation mechanisms - gravitational collapse for heavy ones and disk ejection for light ones.

Together, these results show that brown dwarfs are more than just failed stars. They're a bridge between stellar and planetary populations, with properties that reflect both the Galaxy's history and the diverse ways nature forms substellar objects.
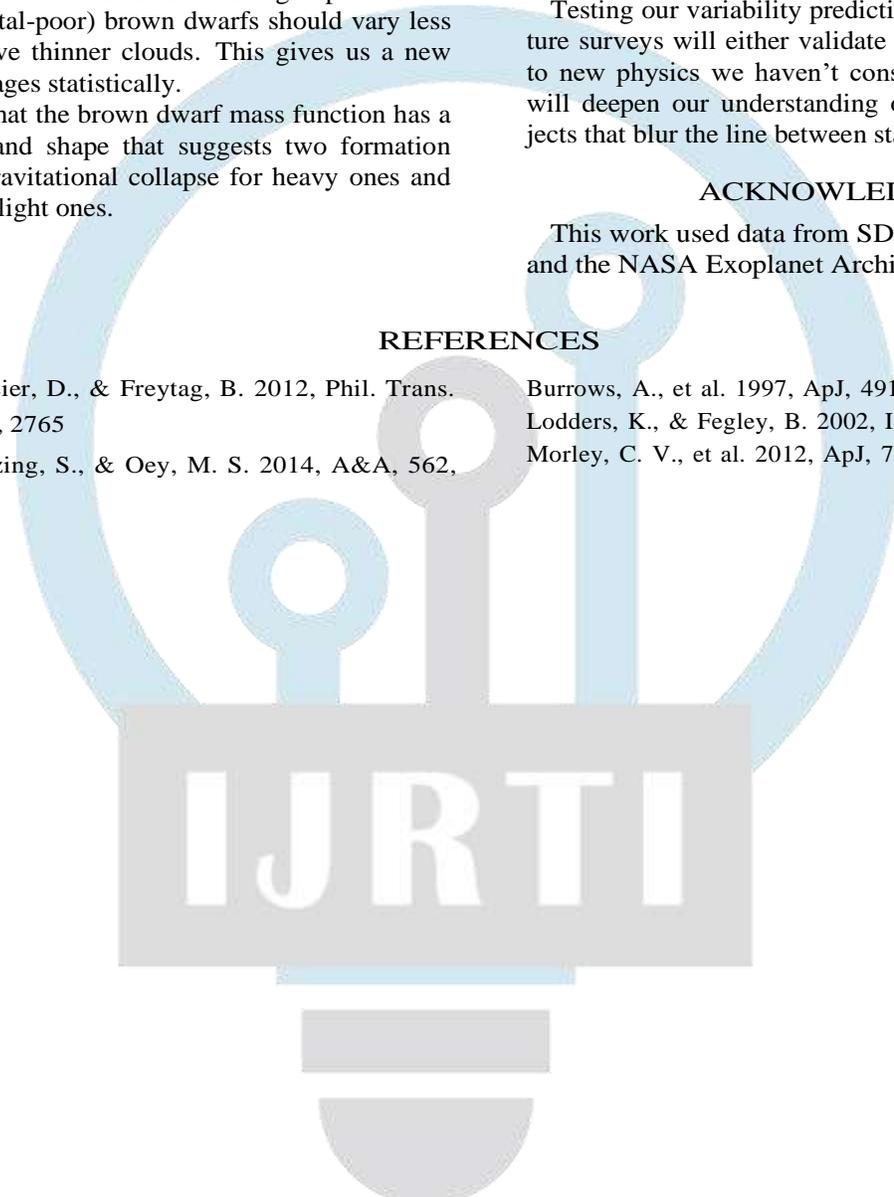
Testing our variability predictions with current and future surveys will either validate this framework or point to new physics we haven't considered. Either outcome will deepen our understanding of these fascinating objects that blur the line between stars and planets.

ACKNOWLEDGMENTS

REFERENCES

Allard, F., Homeier, D., & Freytag, B. 2012, Phil. Trans. R. Soc. A, 370, 2765

Bensby, T., Feltzing, S., & Oey, M. S. 2014, A&A, 562, A71

Burrows, A., et al. 1997, ApJ, 491, 856

Lodders, K., & Fegley, B. 2002, Icarus, 155, 393

Morley, C. V., et al. 2012, ApJ, 756, 172