Matters Arising Submission to Nature Astronomy

Title: *Reconsidering the Origin of TOI-6894b as a Failed Binary Companion*

Authors: R. Scott Johnson

Main Text (≈1100 words): The recent article by Zhang et al. (2025) reports the detection of a Saturn-sized companion, TOI-6894b, orbiting a 0.2 solar mass M-dwarf with a ~3-day period. The authors examine traditional planetary formation models—core accretion and disk instability—and conclude that both are challenged by the object's mass and proximity to its low-mass host star. While the authors emphasize the need to refine models within the circumstellar disk paradigm, they do not consider an alternative scenario that may resolve the tension directly: **TOI-6894b as a failed stellar companion formed via binary fragmentation**.

Hierarchical fragmentation during the collapse of molecular clouds is a well-established formation channel for binary and multiple stellar systems. In this scenario, gravitational instability leads to the division of the collapsing gas cloud into two or more fragments. If the initial mass reservoir is low, or if competitive accretion favors one core over the other, the secondary object may fall below the hydrogen-burning mass threshold (~0.075 solar masses) and become a substellar object. This process can naturally produce brown dwarfs or massive planetary-mass companions without invoking circumstellar disk processes.

For low-mass primary stars like TOI-6894, the distinction between massive planets and low-mass brown dwarfs becomes especially ambiguous. In such systems, binary fragmentation is expected to yield **extreme mass ratios** and **small separations** when total angular momentum is low, particularly in the case of turbulent fragmentation. These systems may appear observationally identical to star–planet systems, but their origins are fundamentally different. In this framing, TOI-6894b is not a giant planet in need of an exotic formation pathway, but a **natural consequence of stellar multiplicity physics operating at the lower edge of the mass function**.

This scenario resolves the central puzzle raised by Zhang et al. without requiring revisions to the efficiency of core accretion or gas accretion lifetimes in ultra-low-mass protoplanetary disks. It also provides a coherent framework for other observed systems with close-in massive companions around M-dwarfs or brown dwarfs, where disk masses are often insufficient to assemble the observed object within the disk-lifetime constraints.

One could object that the current orbital configuration—a close-in circular orbit—disfavors binary fragmentation. However, **post-formation orbital evolution**, including migration via interactions with a circumbinary disk or Kozai–Lidov oscillations followed by tidal circularization, can plausibly bring a substellar companion into a tight, low-eccentricity orbit over gigayear timescales. These same mechanisms are routinely invoked to explain hot Jupiters and short-period binaries in other stellar mass regimes.

It is important to stress that this hypothesis does not violate known statistical distributions of M-dwarf multiplicity. While wide binary fractions decrease with primary mass, recent surveys (e.g., Winters et al. 2019; El-Badry et al. 2021) confirm that tight, low-mass-ratio binaries are not rare among mid-to-late M dwarfs. Indeed, the TOI-6894 system may be part of a **population tail** representing the lower bound of binary fragmentation outcomes, masquerading as planetary systems due to observational mass bias and classification convention.

If accepted, this interpretation would necessitate a re-evaluation of some "giant planets" around low-mass stars, particularly those at or near the deuterium burning limit (~13 MJ). A rigorous assessment of their formation channel—disk vs. fragmentation—would require combining photometric and spectroscopic follow-up with dynamical modeling, chemical abundance comparisons, and statistical inference over multiplicity distributions.

To be clear, we do not claim TOI-6894b *must* be a failed stellar companion—but the omission of this possibility in Zhang et al. is noteworthy. The classification boundary between planets and brown dwarfs remains fuzzy not only in mass but in origin. The present case suggests that adherence to a disk-centric view of planetary formation may blind us to simpler, more astrophysically consistent formation routes, particularly at the low-mass extremes of the stellar main sequence.

We recommend that future analyses of such systems include quantitative modeling of stellar fragmentation and migration histories, especially where the planet-to-star mass ratio exceeds ~ 0.01, or where disk-based formation requires extreme assumptions.

In conclusion, while TOI-6894b may appear anomalous within the canonical planet formation narrative, it is entirely natural within the broader theory of binary star formation. The planet–brown dwarf boundary, long treated as an artificial line in the sand, may be better understood as a **semantic artifact** rather than a true astrophysical divide. Acknowledging this may help resolve not only the formation of TOI-6894b, but a broader class of perplexing systems.

References

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