Why Most Bright Stars are Binary But Most Dim Stars Are Single: A Simple Qualitative Explanation

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Abstract

It is known that most visible stars are binary: they have a nearby companion star, and these two stars orbit around each other. Based on this fact, until recently, astronomers believed that, in general, most stars are binary. A few years ago, a surprising paper showed that while most bright stars are indeed binary, most dim stars are single. In this paper, we provide a simple qualitative explanation for this empirical fact.

1 Why Most Bright Stars are Binary But Most Dim Stars Are Single: An Empirical Fact That Needs to Be Explained

Most visible stars are binary stars: an empirical fact. Since the 18th century, it has been known that many visible stars are binary. As the resolution of the astronomical instruments increased, more and more visible stars turned out to have star companions.

At present, it is estimated that 75-80% of visible stars are binary stars; see, e.g., [1]. From this viewpoint, our Sun is an exception.

Resulting conjecture: most stars are binary. Since most visible stars are binary, astronomers naturally concluded that in general, most stars are binary.

This conclusion led to pessimistic estimates for the number of planets: it is very difficult for a binary star to have a stable planetary orbit, so the natural conclusion was that most stars do not have planets.

Recent observation: most stars are single. Surprisingly, it turns out that most stars are single. This does not contradict to the fact that most visible stars are binary. Indeed, for a star to be visible to a naked eye at a large distance, this star must be sufficiently bright. From this viewpoint, visible stars are bright stars.

However, observations with modern telescopes have shown that most stars are dim, much less bright than our Sun. And it turns out that the vast majority of dim stars are single; see, e.g., [2]. Thus, most stars are single.

An explanation is needed. How can we explain this empirical fact – that most bright stars are binary while most dim stars are single? In this paper, we provide a possible qualitative explanation of this fact.

For this explanation, we need to recall how stars are formed in the first place.

2 How Stars Are Formed: A Brief Reminder

How celestial bodies are formed: a general description. According to astrophysics, in the beginning, matter was reasonably uniformly distributed. However, a uniform distribution is not stable: if we have an excess mass at some point, this excess mass starts attracting matter from nearby regions. Thus, clusters are formed. Clusters grow and merge and eventually, instead of the original reasonably uniform cloud, we have one, two, or more bodies.

Some bodies become stars, some become planets. Depending on the density of the cloud, these bodies have different masses.

If the body's mass is sufficiently large, then the gravitational pressure inside this body becomes large enough to ignite a nuclear reaction, and a star is born. In general, the larger the mass, the brighter the star.

If a body does not have enough mass, it remains a planet. Let us denote the threshold mass separating stars from planets by M_0.

3 Resulting Explanation of the Empirical Fact

Average mass of the resulting bodies. In the above star formation process, the density of the original cloud determines the average mass $\overline{M}$ of the resulting bodies.

The actual masses differ from the average. The actual masses of the resulting bodies may deviate from the average, due to many random factors.

According to the Central Limit Theorem, the joint effect of many independent random factors can be described, with high accuracy, by a normal distribution; see, e.g., [3]. Thus, we can conclude that the masses M_i of different objects have the form $M_i = \overline{M} \cdot \eta_i$, where η_i is a normally distributed random variable with mean 1 and some standard deviation.

If we have two bodies, then the largest has the mass $\overline{M} \cdot \max(\eta_1, \eta_2)$ and the smallest has the mass $\overline{M} \cdot \min(\eta_1, \eta_2)$.

Here, on average, $\eta_1 \approx 1$ and $\eta_2 \approx 1$, so $\min(\eta_1, \eta_2) \approx 1$ and $\max(\eta_1, \eta_2) \approx 1$.

When are both bodies stars? By definition of the threshold M_0, both bodies are stars if and only of the masses of both bodies exceed M_0. This is equivalent to requiring that the mass of the smallest body exceeds M_0, i.e., that $\overline{M} \cdot \min(\eta_1, \eta_2) \geq M_0$ and thus, that

$$\min(\eta_1, \eta_2) \geq \frac{M_0}{\overline{M}}.$$

This explains why most bright stars are binary. The bright stars correspond to large values of the average mass, i.e., to $\overline{M} \gg M_0$. In this case,

$$\frac{M_0}{\overline{M}} \ll 1$$

and, since $\min(\eta_1, \eta_2) \approx 1$, we have, with high probability, $\min(\eta_1, \eta_2) \geq \dfrac{M_0}{\overline{M}}$.

Thus, when $\overline{M} \gg M_0$, with high probability both objects are stars, and we have a binary star.

This also explains why most dim stars are single. By definition, a dim star is a star whose mass is barely above the threshold, i.e., for which

$$\overline{M} \cdot \max(\eta_1, \eta_2) \approx M_0.$$

In this case, for the smaller object, we have

$$\overline{M} \cdot \min(\eta_1, \eta_2) = \left(\overline{M} \cdot \max(\eta_1, \eta_2)\right) \cdot \frac{\min(\eta_1, \eta_2)}{\max(\eta_1, \eta_2)} \approx M_0 \cdot \frac{\min(\eta_1, \eta_2)}{\max(\eta_1, \eta_2)}.$$

Here,

$$\frac{\min(\eta_1, \eta_2)}{\max(\eta_1, \eta_2)} < 1$$

and thus, with high probability, the mass of the smaller object is smaller than the threshold M_0.

So, for dim stars, with high probability, the second body is not a star – and thus, most dim stars are single.

Conclusion. So, our simple model explains why most bright stars are binary, while most dim stars are single.

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