Earth and Planetary Science
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SHORT COMMUNICATION

Mass Comparison of Protoplanetary Disk and Planetary Systems

Aldana Terluk [*] **, *Ricardo Gil-Hutton***

Grupo de Ciencias Planetarias, Departamento de Geofísica y Astronomía, FCEFyN, UNSJ – CONICET, San Juan, J5402DCS Rivadavia, Argentina

ABSTRACT

In recent decades, the number of discovered exoplanets has increased significantly and is expected to continue growing due to advancements in detection methods. Simultaneously, the study of protoplanetary disks has enabled the estimation of dust mass in various star-forming regions. Since these disks serve as the birthplace of planetary systems, a combined analysis of exoplanets and disks can improve our understanding of planet formation and evolution. In this paper we compare existing estimates of dust mass in protoplanetary disks with the solid mass in known exoplanetary systems to estimate the initial solid mass required to form the observed population of planets. First, the total masses of exoplanetary systems are calculated and these values are then compared with the estimated dust mass in protoplanetary disks. The results indicate that in most cases the solid mass of exoplanetary systems exceeds the expected mass of their original disks. Furthermore, it is found that early-stage disks (Class 0 and Class I) may contain approximately 100 times more dust than those in more evolved stages (Class II). Finally, the results obtained also suggested that the solid mass of observed planetary systems could be limited to a maximum of 500 $M_{\oplus}$, which may constrain the growth of rocky planets and the accumulation of material in the cores of giant planets.

Keywords: Exoplanets; Protoplanetary Disks; Planetary Systems

*CORRESPONDING AUTHOR:
Aldana Terluk, Grupo de Ciencias Planetarias, Departamento de Geofísica y Astronomía, FCEFyN, UNSJ – CONICET, San Juan, J5402DCS Rivadavia, Argentina; Email: aldana41292@gmail.com

ARTICLE INFO
Received: 8 February 2025 | Revised: 13 March 2025 | Accepted: 27 March 2025| Published Online: 3 April 2025
DOI: https://doi.org/10.36956/eps.v4i1.1955

CITATION
Terluk, A., Gil-Hutton, R., 2025. Mass Comparison: Protoplanetary Dust and Planetary Systems. Earth and Planetary Science. 4(1): 66–72. DOI: https://doi.org/10.36956/eps.v4i1.1955

1. Introduction

Over the past few decades, the number of confirmed exoplanets has increased significantly, and this figure is expected to continue rising, revealing an extraordinary diversity of planetary system architectures. In parallel, substantial progress has been made in the study of protoplanetary disks, leading to a deeper understanding of their physical properties and the estimation of dust masses across various star–forming regions [1–8] and in some open clusters [9,10]. Since protoplanetary disks represent the birth environment of planetary systems, jointly studying them with exoplanets provides a valuable opportunity to link the initial conditions of disk evolution to the final outcomes of planet formation.

One of the most critical parameters in models of planet formation is the mass of the disk, as it largely determines both the number and the total mass of planets that can be form [3]. Observations with ALMA, supported by optical and near-infrared spectroscopic, have facilitated the estimation of dust mass in protoplanetary disks. These estimates form the basis for assessing whether the dust content of disks is consistent with the solid mass found in observed planetary systems.

Recent studies have established quantitative relationships between disk properties and the characteristics of their host stars. Williams and Cieza [11] compiled submillimeter observations of disks around Class II young stellar objects and found that disk masses are generally lower for low-mass stars, with a trend of $M_{\mathrm{disk}}/M_{\mathrm{star}} \sim 0.01$. They showed that nearly all disks around stars with masses between 0.04 to 10 $M_{\odot}$ fall within ±1 dex of this ratio. Expanding on this, Pascucci et al. [3] analyzed disk in the Chamaeleon I region and found a power-law relation of the for $M_{\mathrm{dust}} \propto M_{\mathrm{star}}^{1.6\pm0.3}$. This exponent suggests a possible link between average dust temperature and stellar luminosity. Moreover, similar dust–stellar mass relationships have been found in the other regions such as Taurus and Lupus, while the older Upper Scorpius association (~10 Myr) shows a steeper trend.

Testi et al. [12] further investigated Class II/F disks in the L1688, the densest and youngest star-forming region of Ophiuchus, and compared their findings with other regions. Their study evaluated stellar properties (e.g., stellar and age) an disk properties (e.g., gas accretion rates and dust masses), showing that the dust mass follows a power -law relation with stellar mass, expressed as $\log_{10}(M_{\mathrm{dust}}/M_{\oplus}) = \alpha + \beta \log_{10}(M_{\mathrm{star}}/M_{\odot})$, whit α and β varying across different stellar populaition. These results reinforce the idea that disk mass, particularly dust mass, is closely linked to the mass of the central star and provide a compelling framework for assessing planet formation potential in diverse environments.

However, most dust mass estimates rely on converting observed flux to mass using model-dependent methods that assume optically thin emission, fixed values for opacity and temperature, and a uniform dust-to-gas ratio. This approach introduces significant uncertainties due to variations in chemical composition, disk structure, and stellar age, often leading to underestimates of the true disk mass. Alternative techniques, such as using "dust lines" [13], tend to yield higher mass estimates, reflecting the inherent difficulty in accurately measuring dust mass in protoplanetary disks.

To derive total disk mass (gas + dust), studies typically assume a dust-to-gas ratio of 1%. Yet, some evidence suggest that this ratio could be higher [14,15], which important implications for the availability of material to forms planets. Therefore, accurately determining the dust-to-gas ratio remains an open challenge. Moreover, assuming that Class II disks represent the typical sites of planet formation, the total available material often appears insufficient to explain the observed masses of planetary systems. This discrepancy is known as the mass budget problem [16].

Greaves and Rice [17] and Najita and Kenyon [18] pointed out that only a fraction of observed disks contain enough mass to form known exoplanetary systems. Similary, Mulders et al. [19,20] using Kepler data, found that the estimated disk masses around low-mass stars are generally smaller heavy-element content observed in their planetary systems. Manara et al. [21] compared disk masses with the total mass of confirmed exoplanetary systems and concluded that the planetary system masses are often equal to or even exceed those of the most massive disks. These findings remain consistent when planetary masses are converted to their solid content (e.g., core masses for gas giants, total masses for super-Earths).

A proposed solution to the mass budget problem is early planet formation, ocurring before the Class II stage. This hypothesis is supported by recent high-re solution observations that reveal substructures—such as rings and gaps—in disks younger than 1 Myr, possibly indicating that the planet formation processes are already underway [22,23]. In this scenario, the earlier Class 0 and Class I phases become relevant. Tychoniec et al. [24] argue that these earlier disk may contained more dust mass, potentially enough to account for entire planetary systems.

Savvidou and Bitsch [16] explored the evolution of dust during planet formation and concluded that current dust mass estimates may represent lower limits and that early planet formation is essential, especially for the formation of gas giants. Two main possibilities have been proposed to explain the missing mass: (1) disk masses may be underestimated due to model assumptions or unaccounted contributions from optically thick regions; or (2) Class II disks represent a later evolutionary stage in which much of the solid material has already been incorporated into planetesimals or planets—leaving only the residuals of the formation process.

In both cases, understanding the earliest stages of disk evolution is essential for resolving the origin of planetary systems. Assuming that early planet formation is the more plausible explanation, this study compares the dust mass of protoplanetary disks with the solid mass found in known exoplanetary systems and its goal is to estimate the initial amount of solid material required to form planetary systems. Section 2 describes the exoplanet sample used and calculates the total mass of the exoplanetary systems. In Section 3, system masses are compared with the existing estimates of dust mass in protoplanetary disk and Section 4 presents the conclusions.

2. Materials and Methods

Exoplanet Sample

For this study, exoplanet data were obtained from the NASA Exoplanet Archive (as of Sep 24, 2024). Objects were selected based on the availability of both planetary mass and the mass of their host star. No filters were applied regarding the detection method, mass measurement technique, or spectral type of the host star. A total of 5759 exoplanets with known mass value were identified, either as actual mass or as lower limit ($M \times sin(i)$). Of these, 4866 planets have estimated mass (either measured directly or inferred using radius-to-mass relationships), while 893 have only a minimum mass estimates.

To estimate the total mass of each exoplanetary system, the masses of the individual planets within the system were summed. Since the analysis focuses specifically on the dust content in protoplanetary disks, it is consistent to consider only the heavy-element content of the planets, as these are the components most closely associated with the solid phase of the disk.

Following a standard approach, rocky planets were defined as those with masses less than 10 Earth masses ($M_{PL} < 10M_{\oplus}$) and their total mass was taken as a direct proxy for the system's heavy-element content. For more massive planets ($M_{PL} \geq 10M_{\oplus}$), their masses were converted into core (i.e., solid) masses using the relation proposed by Thorngren et al. [25], given by: $M_{\mathrm{C}} = 57.9\ (M_{\mathrm{PL}})^{0.61}$, where M_{C} is the heavy-element mass in Earth masses and M_{PL} is the planetary mass expressed in Jupiter masses. This relation is based on structural and thermal evolution models that link a gas giant's metallicity to its total mass. Using this method, the core masses of 2667 giant planets were estimated.

The total heavy-element mass of each exoplanetary system was then calculated by summing the masses of the rocky planets and the core masses of the giant planets in the system.

It is important to note that the estimated masses of the exoplanetary systems may evolve with future discoveries, as additional planets are detected in already known systems. However, this effect is expected to be minor, since undetected planets are generally of lower mass and contribute only marginally to the total system mass. Nonetheless, this contributes to the observed dispersion in system masses for a given stellar mass [21].

3. Results

Comparison between Protoplanetary Disk and Exoplanetary Systems Masses

Figure 1 shows the solid mass of planetary systems as a function of their host star's mass. As expected, most of the exoplanetary systems lie below the M_{disk}/M_{star} = 0.01 line, since planets form from only a fraction of the original protoplanetary disk. Both observation and theorical models indicate that only a limited portion of the disk mass is converted into a planets, while a significant fraction is either dissipated, accreted by the host star, or otherwise prevented from forming planetary bodies due to various physical mechanisms. Thus, the total planetary mass in a system is generally less than the original disk mass.

However, for low-mass stars ($M_{star} < 0.3M_{\odot}$), 46 systems lie above or close to the M_{disk}/M_{star} = 0.01 line. These systems typically host a single massive planet ($M_{pl} \geq 10M_{\oplus}$), with some objects exceeding 13 M_J acording to catalog data. Manara et al. [21] suggest that these systems may have formed via binary formation processes rather than standard planet formation. Although listed as exoplanets in catalogs, many of these objects surpass the conventional upper mass limit for planets, raising questions about their true nature and blurring the distinction between giant planets, brown dwarfs, and low-mass stellar companions. As a result, these systems are excluded from the subsequent analysis (Although these systems are not included in the analysis, they are presneted in all figures for the sake of completeness.)**.**

It is also worth noting that **Figure 1** highlights a potential upper limit for the solid mass in planetary systems: almost all systems, including those with very massive planets, remain below a total solid mass of approximately 500 $M_{\oplus}$. The few multi-planet systems found above the 500 $M_{\oplus}$ line may result from uncertainties in the determination of planetary masses or in the estimation of the solid mass for massive planets. In any case, this may suggest a physical or observational limit for the solid mass content in exoplanetary systems.

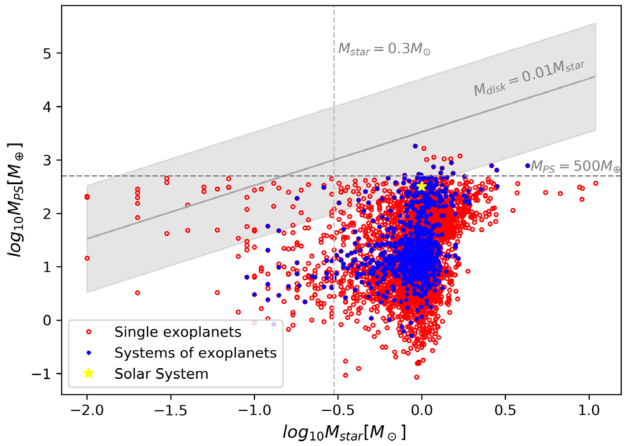

Figure 1. Masses of exoplanetary systems as a function of the host star mass. The solid diagonal line represents the relation $M_{disk} = 0.01M_{star}$, and the shaded area in gray, ±1 dex around this relation.

To compare planetary system masses with the dust mass in protoplanetary disks, we adopted the empirical relations provide by Testi et al. [12] for different star-forming regions. The parameters for each region are summarized in **Table 1**. **Figure 2** again displays the relationship between planetary system mass and host star mass, alongside the corresponding disk mass estimates for various regions. As shown in the figure, the relations for different star-forming regions exhibit significant dispersion and, then, they do not provide a single, unified representative relation that can be used to compare with the observed planetary systems.

Table 1. Power-law parameters for the M_{dust} vs. M_{star} relation: $\log_{10}(M_{dust}/M_{\oplus}) = \alpha+\beta \log_{10}(M_{star}/M_{\odot})$ for different star-forming regions. The value of δ is a measure of the fit dispersion. Table adapted from Testi et al. [12].

Region	α	β	δ
Corona Australis	0.4 ± 0.4	1.3 ± 0.5	1.1 ± 0.7
Taurus	1.1 ± 0.1	1.5 ± 0.2	0.8 ± 0.3
L1688	1.0 ± 0.1	1.5 ± 0.2	0.8 ± 0.3
Lupus	1.4 ± 0.2	1.7 ± 0.3	0.7 ± 0.3
Chamaleon I	1.1 ± 0.2	1.6 ± 0.3	0.7 ± 0.4
Upper Scorpius	0.8 ± 0.2	2.2 ± 0.3	0.7 ± 0.3

To obtain a representative dust mass-stellar mass relation, we calculed the average of the five relation corresponding to the Corona Australis, L1688, Taurus, Lupus, and Chamaeleon I. The Upper Scorpius region is excluded from due to its older age and significantly lower dust content. To obtain an estimation for this representative relation, we applied a weighted least-squares approach, combining the individual α and β values derived for each region and using their respective uncertainties as weights. The resulting parameters for the dust mass–stellar mass relation are $\alpha_m = 1.073 \pm 0.06$ and $\beta_m = 1.53 \pm 0.11$.

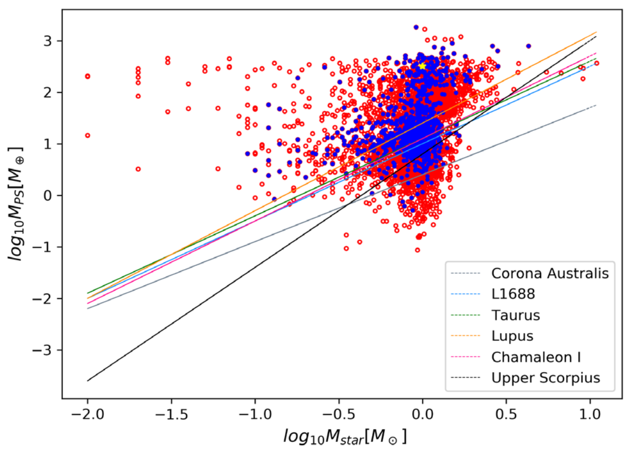

Figure 2. Masses of exoplanetary systems as a function of the host star, along with the relation M_{dust} vs. M_{star} for the different star formin regions (see text), reported by Testi et al. [12].

A notable fraction of planetary systems exhibit solid masses that exceed the estimated dust mass of their corresponding disks. This discrepancy likely arises from the fact that Testi et al. [12] focus on evolved Class II disks, and therefore their estimates do not reflect the higher initial dust content expected in younger, Class 0 disks.

To estimate the mass of Class 0 disks, we seek the multiplicative factor by which the average Class II disk mass must be increased to ensure that the mass of most planetary systems remains below the corresponding disk dust mass. In **Figure 3**, the green line represents the average dust mass estimate for Class II disks. The three additional curves, shown in violet, light blue, and orange, represent this estimate multiplied by factors of 15, 50, and 100. The scalling factors of 15 and 50 are based on results previous findings suggesting that Class 0 disks contain approximately 15 to 50 times more dust than Class II disks [6] and were included for comparison. The factor of 100 on the other hand, provides a good compromise for most planetary system masses and was chosen so that, when multiplying the average relation by this factor, most of the scattered points lie below this line. This result suggest that early disks may contain at least two orders of magnitude more solid material than those at later stages.

Based on this estimate, and considering the observed upper limit of ~500 $M_\oplus$ for planetary systems masses, the difference between the difference between the inferred initial disk mass and the final planetary mass may offer an estimate of the amount of solid material lost during disk evolution.

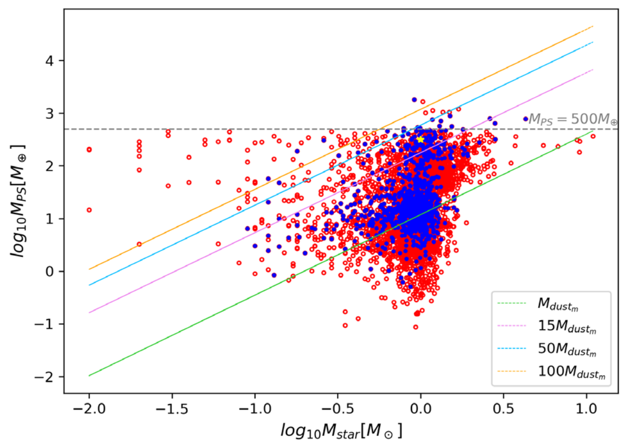

Figure 3. Masses of exoplanetary systems as a function of the host star mass. The green curve represents the average relation between dust mass in Class II disks and stellar mass. This average relation is scaled by factors of 15, 50, and 100. The first two scaling factors correspond to estimates for Class 0 disks previously reported in Tychoniec. et al. [24], based on ALMA and VLA observations, respectively.

4. Conclusions

The masses of exoplanetary systems were compared with a relation representing the dust mass in Class II protoplanetary disks as a function of the central star's mass, based on the various correlations established for differentstar-forming regions by Testi et al. [12].

This comparison show that the Class II disk mass relation alone is insufficient to account for the observed exoplanet population. A significant number of exoplanetary systems, both single-planet and multi-planet systems, have solid masses that exceed the expected dust mass of their disks. To reconcile the solid mass in observed planetary systems, it is necessary to increase the mass in Class II disks by a factor of at least 100. This factor applies to the total solid mass budget and enables the estimation of the minumun mass that disks as the beginning of their evolution (Class 0/I disks) must have to eventually form a planetary system.

The results of this study suggest that disks in the earliest evolucionary stages (Class 0 and Class I) may contain at least 100 times more dust than those in the more evolved Class II stage. This estimate is considerably higher than the one previously reported by Tychoniec et al. [24]. It is worth mentioning that this factor corresponds to the solid mass of the disk for the most massive planetary systems; less massive planetary systems could form from less massive disks (factors lower than 100).

Moreover, the fact that most planetary systems have total solid masses of $M_{\rm PS} \leq 500 M_{\oplus}$ may point to an upper limit on the solid mass content of exoplanetary systems. Such a limit could constrain the formation and growth of rocky planets, as well as the accumulation of solid material in the cores of giant planets.

Finally, the group of objects orbiting around low-mass stars with masses significantly exceeding 13 $M_{\rm J}$ warrants further investigation to understand their origin and to distinguish between potential object types.

Author Contributions

Conceptualization, A.T. and R.G.-H.; methodoly, A.T. and R.G.-H.; formal analysis, A.T.; investigation, A.T.; writing, A.T. and R.G.-H.. All authors have read and agreed to the published version of the manuscript.

Funding

The authors gratefully acknowledge financial support by CONICET through PIP 112-202001-01227 and San Juan National University by a CICITCA grant for the period 2023–2025.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Publicly available datasets were analyzed in this study. This data can be found here: https://exoplanetarchive.ipac.caltech.edu.

Acknowledgments

We thank the anonymous reviewers for their helpful suggestions and comments.

Conflicts of Interest

The authors disclosed no conflict of interest.

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