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Detection and characterization of exoplanets from the Pico dos Dias Observatory: recent results from gravitational microlensing events

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Abstract. This study highlights the observational capabilities of the Pico dos Dias Observatory (OPD) in the detection and characterization of exoplanets through gravitational microlensing events. We present the results of observations conducted over the past three years using the Perkin&Elmer-1.6m and Boller&Chivens-0.6m telescopes. In particular, we emphasize the detection of Gaia22dkvLb, which was identified following an alert from the Gaia mission in August 2022, succeeded by a series of observations involving a global network of telescopes, including the OPD. The analysis suggests that Gaia22dkvLb is a jovian planet with an estimated mass of 0.59±0.15 M_J and a projected separation of 1.4±0.8 AU from its host star, located approximately 1.3 kpc away. The OPD plays a crucial role in survey campaigns that enable the detection of gravitational microlensing events, providing essential data for the detailed modeling of the light curves of these events. The applied methodology involves precision photometry and advanced modeling techniques. This approach facilitates the detailed characterization of detected planets and opens new avenues for complementary observations, such as radial velocity measurements for events with brighter host stars, exemplified by the case of the star Gaia22dkv. Over the past three years, the OPD has participated in several detections of exoplanets and binary systems, demonstrating the efficacy of combining data from space missions and terrestrial observatories. These international collaborations and the use of multiple telescopes underscore the importance of the OPD in the detection and characterization of exoplanets, significantly contributing to the understanding of planetary demographics in the Galaxy.

Resumo. Este estudo destaca as capacidades de observação do Observatório Pico dos Dias (OPD) na detecção e caracterização de exoplanetas através de eventos de microlente gravitacional. Apresentamos os resultados de observações realizadas nos últimos três anos usando os telescópios Perkin&Elmer-1.6m e Boller&Chivens-0.6m. Em particular, enfatizamos a detecção do Gaia22dkvLb, que foi identificado após um alerta da missão Gaia em agosto de 2022, sucedido por uma série de observações envolvendo uma rede global de telescópios, incluindo o OPD. A análise sugere que Gaia22dkvLb é um planeta joviano com uma massa estimada de 0,59±0,15 M_J e uma separação projetada de 1,4±0,8 UA de sua estrela hospedeira, localizada aproximadamente a 1,3 kpc de distância. O OPD desempenha um papel crucial em campanhas de pesquisa que permitem a detecção de eventos de microlente gravitacional, fornecendo dados essenciais para a modelagem detalhada das curvas de luz desses eventos. A metodologia aplicada envolve fotometria de precisão e técnicas de modelagem avançadas. Essa abordagem facilita a caracterização detalhada dos planetas detectados e abre novas possibilidades para observações complementares, como medições de velocidade radial para eventos com estrelas hospedeiras mais brilhantes, exemplificado pelo caso da estrela Gaia22dkv. Nos últimos três anos, o OPD participou de diversas detecções de exoplanetas e sistemas binários, demonstrando a eficácia da combinação de dados de missões espaciais e observatórios terrestres. Essas colaborações internacionais e o uso de múltiplos telescópios reforçam a importância do OPD na detecção e caracterização de exoplanetas, contribuindo significativamente para o entendimento da demografia planetária na galáxia.

Keywords. Gravitational lensing: micro, (Stars): planetary systems, Techniques: photometric

1. Introduction

The method of Gravitational Microlensing (GM) depends on the fact that gravity can be characterized as the curvature of spacetime. Hence, a light ray traveling through space will have its path deflected when passing near the gravitational field of a star (Einstein 1936). If there is an almost alignment between a background star (source), an intermediate star (lens), and the observer, the intermediate star will act as a "lens" and we will see an increase in the source's brightness. This alignment is time-dependent, resulting in a light curve that shows the variation of the source's light over time (Liebes 1964; Paczynski 1986; Mao & Paczynski 1991).

Analyzing this light curve and applying the equations of GM theory (Almeida, L 2017, 2021), we can infer the characteristics of the lens that cause this variation in the light curve. If we analyze a GM event from a star that hosts a planet (or even another star), we can directly determine the relationship between the masses of the system and the apparent separation between the planet and the star through light-curve modeling. Beyond characterizing exoplanets, other interesting outputs include determining the limb darkening of the source, anomalies in the distribution of the source star, and the measurement of the source's angular dimensions itself.

Since 2018, using the telescopes of the Pico dos Dias Observatory (OPD), we have participated in the MicroFun collaboration with Ohio State University (Gaudi 2012), which is a network of small and medium telescopes that photometrically follow GM events towards the center of our galaxy. The network does not independently search for GM events, but utilizes those discovered by the OGLE, MOA, and KMTnet collaborations (Sumi et al 2006; Bond et al. 2001; Kim et al. 2016). Due to the OPD's unique position without any other observatories at the same longitude, all observations made from this location are crucial for acquiring a continuous and uninterrupted light curve (see figure 1. Since 2021, in addition to observations, we have actively participated in modeling and the general discussion of articles, representing OPD in this collaboration. Each year, approximately 15 to 20 GM events are observed using the Perkin & Elmer (PE), Boller & Chivens (BC), and Zeiss (ZE) telescopes at OPD. In this work, we provide a comprehensive overview of the

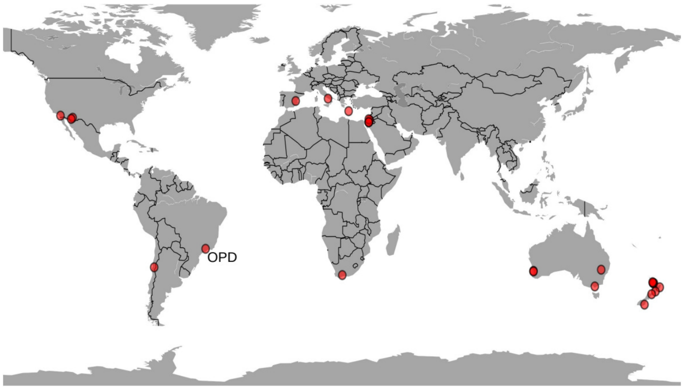

Figure 1. Map of the world showing in red all the observatories that are part of the MicroFUN collaboration.

significant role played by the telescopes at the OPD in detecting and characterizing GM events. These events are a focal point of our collaboration with the MicroFun network, with the aim of achieving a deeper understanding of exoplanet occurrences within our galaxy. In addition, we present a selected compilation of the most significant publications from the last three years that originated from this project. These detections serve as a testament to the productive synergy within the collaboration and the key contributions of the OPD's telescopic capabilities.

2. OPD capabilities

The Pico dos Dias Observatory, managed by the National Astrophysics Laboratory (LNA) in Brazil, contributes significantly to the observation of microlensing events. It operates as part of a global effort to observe these transient events which provide vital insights into the distribution of exoplanets in our galaxy. The OPD is equipped with three main telescopes, each one with unique capabilities and specifications. They are made available to the Brazilian astronomical community semiannually through the submission of observational proposals.

The largest telescope in Brazil is the Perkin & Elmer (PE), which is a telescope with Ritchey-Chretien optics and a 1.6-meter primary mirror. Currently, the PE telescope is equipped with the SPARC4 instrument (The Simultaneous Polarimeter and Rapid Camera in Four Bands)(Rodrigues et al. 2012, 2024). SPARC4 provides world-class rapid photometry and polarimetry in the four SDSS bands simultaneously, with a field of view of 5.7 x 5.7 $arcmin^2$. Developed by the National Institute for Space Research (INPE) in collaboration with LNA and other Brazilian universities and institutes, SPARC4 enhances observation efficiency and employs differential techniques in both photometry and polarimetry. Before the comissioning of SPARC4, the PE telescope was equipped with direct cameras such as Andor Ikon and Ixon to do photometry. Today, only SPARC4 and the COUDE spectrographer are used in this telescope. Both SPARC4 and direct cameras were used in GM campaigns. The Boller & Chivens telescope is a 0.6 meter telescope also with Ritchey-Chretien optics. It can be equipped with direct cameras and with a polarimeter. With the use of a Andor Ikon CCD with 2048 x 2048 pixels, this setup achieves a field of view of approximately 12 arc-minutes. The Zeiss telescope is also a 0.6 meter telescope but with a parabolic primary mirror. It can mostly hold direct cameras for photometry. The Zeiss telescope has been part of the history of GM events detections by OPD in the last 15 years. Before 2020 the OPD telescopes participated in several publications in GM detections of exoplanets and binary stars (Bachelet et al. 2012; Hwang et al. 2013; Kains et al. 2013; Han et al. 2013; Bachelet et al. 2015; Skowron et al. 2015).

3. Methodology

3.1. Observing with OPD telescopes

Before the start of each observation night, it is essential to define the targets to be monitored. This definition is based on the alerts sent by the MicroFUN collaboration. During the day or the previous night, potential GM events are communicated via email to all observatories in the network. GM events are initially discovered by the OGLE and MOA collaborations, which monitor thousands of stars in the galactic center between April and September. These surveys produce thousands of GM events annually. However, the low cadence of observations conducted by these surveys limits their ability to detect exoplanet signals. Alerts are issued when anomalies are detected in the light curves, such as deviations from the characteristic shape of single-lens GM events, or when the predicted magnification of the event is exceptionally high. These anomalies may indicate the presence of planets around the lens. The alerts include detailed information on the position and magnitude of the event, as well as the light curve and the best model at the time of the alert issuance. Upon receiving an alert, the observatories organize their observation nights, prioritizing these targets. During observation, telescopes around the world monitor the same event in a coordinated manner, allowing for continuous and global coverage of the phenomenon. This approach increases the likelihood of detecting subtle signals associated with the presence of exoplanets. At the end of each observation night, the collected data must be processed and quickly sent to the collaboration, so that the evolution of the event can be evaluated and the models refined. This joint effort enables the achievement of high-quality results and contributes to the advancement of research in GM and exoplanets.

The observation nights at the Pico dos Dias Observatory (OPD) follow a structured routine that ensures the efficiency and quality of the acquired data. Initially, the telescope is aimed at the desired target using the right ascension (RA) and declination (DEC) coordinates, which are entered into the Telescope Control System (TCS). After configuring and adjusting the position with commands like 'PRECESS' and 'POINT', the target should appear centered in the acquisition system's field of view. Depending on the instrument (SPARC4 or direct camera), the procedure is significantly different, so we will not discuss this here. To optimize tracking, the 'autoguider' system is activated, which continuously adjusts the telescope based on the position of a selected guide star in the observed field. The parameters of the autoguider, such as exposure time (T-exp), correction (T-corr), number of boxes (nBox), and sigma, are adjusted to ensure accuracy, considering the magnitude of the field stars. During gravitational microlensing (MG) event observations, the exposure time is set according to the event's evolution and the target's magnification. Typically, 60-second exposures are used, reducing this value to prevent saturation in cases of high magnification. The observation strategy prioritizes high-relevance alerts, dedicating one continuous hour to the main target. After this period, 15 to 20 minutes observations are made on lower priority targets, alternating between them throughout the night. This cycle allows for an efficient balance between collecting priority data and exploring other observational events. This structured process ensures that the data obtained in OPD are consistent and contribute significantly to the analysis of the GM event.

3.2. Data Reduction and Submission Process

At the end of each observation night, the reduction in data begins to make it suitable for submission to the MicroFUN collaboration. This procedure is crucial to ensure that the data are in an appropriate format for subsequent analyses and modeling. The process starts with 'flats' and 'bias' correction and image cropping to reduce the size of fits files. This step aims to expedite the submission of data, which should occur the next morning since alert updates depend on observations from the previous night. Initially, the shift in the captured images is determined. Even with a well-adjusted autoguider system, slight shifts can occur as a result of changes in the pointing between different targets. We develop a Python pipeline that identify and correct these shifts, perform a basic photometric analysis to detect the main stars in each frame, generating a shift table used for center correction. Once the shifts are corrected, the calibration master files are created. Bias master and flat master files are generated by combining the respective frames within the pipeline, using commands to normalize and adjust the images according to the average parameters of the collected data. These calibration files are applied to scientific images to correct artifacts and ensure data uniformity. Finally, images are cropped to reduce size, preserving only the area of interest. All these steps are performed within the pipeline. Reduced images are named in a standardized manner and organized for submission. The finalized image set is ready for upload, ensuring data readiness for analysis by other collaboration members. This structured workflow maximizes the efficiency and quality of the data shared.

In 2018, the MicroFUN Collaboration standardized the procedures for submitting observations made by various observatories. This process aims to optimize data integration and analysis. The first step involves creating a reference image of the target using observations from the previous night. This image, called find-chart.jpg, should have the target centered with a cross added for identification, and can be generated using any image editing software. Then, a file named 00README.txt is prepared to include basic information about the observation, such as the date, the telescope, and detector used, the orientation and size of the detector pixels, and a list of all fits files to be submitted. After preparing the files, the data is organized into a compressed folder following the convention siteCode-eventID-utcDate, where: siteCode refers to the observatory code (e.g., OPD06 for the 0.6m telescope and OPD16 for the 1.6m telescope); eventID identifies the observed event; utcDate is the UTC date in the format YYMMDD. The compressed files include find-chart.jpg, 00README.txt, and all reduced images. For submission, the MicroFUN FTP server is accessed using credentials provided by the collaboration. Data are transferred to the appropriate directory, generally using specific commands to ensure transfer integrity. After uploading, an email is sent to the MicroFUN coordination team detailing the completed observation and upload status. This standardized procedure ensures that data from all observatories are consistent, facilitating integration in the joint analyses carried out by the MicroFUN collaboration.

4. Results

This section presents results from several exoplanet studies conducted during and after the COVID-19 pandemic. These include the discovery of an Earth-mass planet orbiting a star during logistical challenges imposed by the pandemic, and a notable exoplanet detected outside the galactic bulge with prospects for radial-velocity characterization. The section also details a microlensing planet with a mass less than 10 detected through subtle observational signatures and precise measurements of a brown dwarf's mass in a binary system. The discoveries fill gaps in our understanding of exoplanet demographics, particularly systems with very low mass ratios.

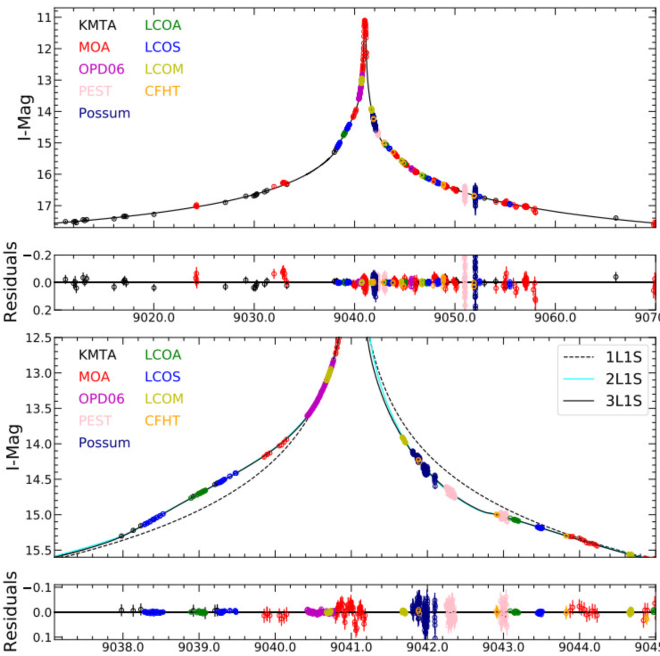

Figure 2. Light curve of KMT-2020-BLG-0414 with lensing models as shown in published paper. The circles with different colors are the observed data points for different data sets. The black solid line is the best-fit 3L1S model incorporating all the data, the cyan solid line is the best-fit 2L1S model excluding the MOA data on the peak and the black dashed line is the 1L1S model.

4.1. An Earth-mass planet in a time of COVID-19

The paper "An Earth-mass planet in a time of COVID-19: KMT-2020-BLG-0414Lb" (Zang et al. 2021) was the first exoplanet discovery publication using the GM method after 2020, where we reported the discovery of an exoplanet with a mass similar to Earth's orbiting a star with approximately 0.3 $M_{\odot}$. This event was observed during the worst phase of the COVID-19 pandemic, which imposed significant logistical challenges due to the temporary closure of most observatories. We played a crucial role in the observational data, as we conducted observations from the Pico dos Dias Observatory and also remotely using the BC and PE telescopes. These observations were essential, especially during the phase when the anomaly in the light curve was detected, and we were able to perform high-cadence observations. Moreover, we actively participated in the discussion of the details as well as the preliminary modeling of the event, helping to interpret the data and refine the models describing the discovered system. The modeling involved analysis of the light curve using binary and triple microlensing models, revealing that the system was composed of 3 bodies: a host-star with approximately 0.3 times the mass of the Sun; a planet with Earth's mass; and a third component with about 17 times the mass of Jupiter possibly being a brown dwarf. Figure 2 shows the observational data fitted with one lens and one source (1L1S), two lenses and one source (2L1S) and with three lenses and one source (3L1S) model.

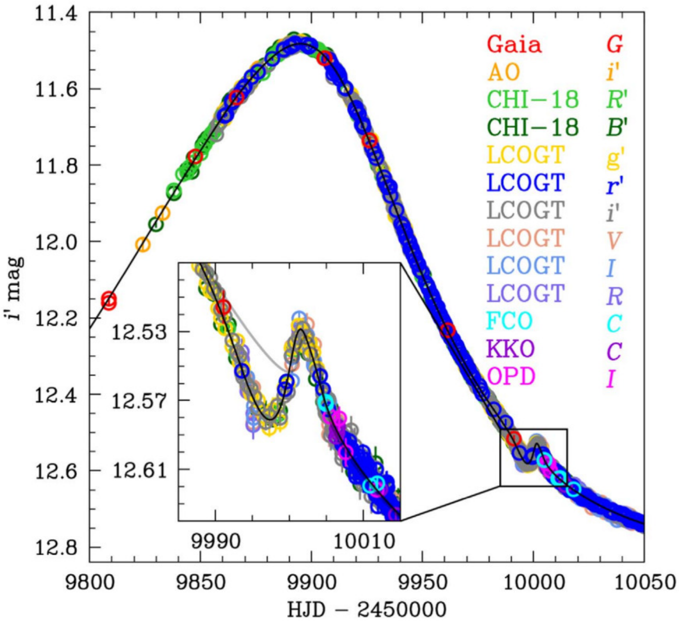

Figure 3. Gaia22dkv's light curve and the best-fit planetary microlensing model (black solid line) considering microlens parallax and orbital motion effects. Data points observed by various sites are shown as open circles in different colors, respectively.

The results we obtained challenge the existence of the so-called 'break point' in the mass ratio function (q), which had been previously suggested to explain the scarcity of multiple systems with very low mass ratios. This exoplanet's discovery, along with other recent findings, fills a previously empty area in the 'mass vs. semi-major axis' diagram, suggesting that the detection of exoplanets with low mass ratios is due to detection difficulty rather than scarcity of these systems.

4.2. Gaia22dkvLb

The paper "Gaia22dkvLb: A microlensing planet potentially accessible to radial-velocity characterization" (Wu et al. 2024) was our second exoplanet detected using microlensing (MG) after 2020, in an event detected by Gaia in August 2022, and alerted for MicroFun in March 2023. This event is particularly notable for occurring outside the galactic bulge, revealing an exoplanet at a distance of approximately 1.3 kpc from Earth. The host star stands out for being considerably brighter (14 in the r band) than most of the GM systems observed. This is important as it opens new opportunities for system characterization via radial velocity (RV) observations. At OPD, we secured observational time shortly after the MicroFun alert because we usually do not request nights from September to April due to the galactic center not being visible. We conducted observations with the PE and BC telescopes and participated in the pre-analysis of the event for preliminary system characterization, as well as in the discussion for the article's preparation. The event analysis includes both the annual parallax effect of Earth and the orbital motion of the exoplanet. We used the binary microlensing model with a single source to fit the observed anomaly in the light curve. Figure 3 shows the observational data with the fitted model.

The characterized exoplanet, Gaia22dkvLb, is a gas giant with an estimated mass of 0.59 Jupiter masses, orbiting a star of 1.1 $M_{\odot}$ at approximately 1.4 astronomical units. One of the most exciting aspects of this discovery is the potential for additional characterization with RV, as usually MG-detected systems have very dim hosts. Spectroscopic observations of this star and consequently RV data can provide details regarding the planet's orbital period and its eccentricity, which are parameters not easily accessible with MG. The application of RV also enables the search for additional planets in the system, especially those orbiting closer to the host star. This publication contributes to mapping the demographics of exoplanets in our galaxy, helping bridge the gap between planets detected by GM (generally beyond the ice line) and those discovered by RV and planetary transits (usually much closer to their stars).

4.3. KMT-2023-BLG-1431Lb

In this study entitled: "KMT-2023-BLG-1431Lb: A New $q < 10^4$ Microlensing Planet from a Subtle Signature", we report the detection and analysis of a planetary event by GM, KMT-2023-BLG-1431, with a subtle and short-duration planetary signature, characterized by follow-up from KMTNet and LCO (Bell et al. 2024). The 2L1S model reveals a planet/host mass ratio and excludes the 1L2S model. Bayesian analysis using a Galactic model estimates the host star mass, planetary mass, and lens distance. We find that without follow-up data, survey-only data cannot resolve certain degeneracies. Part of the observations were also conducted with OPD telescopes, highlighting the importance of follow-up in current microlensing surveys.

4.4. OGLE-2019-BLG-0033/MOA-2019-BLG-035

In this study, titled "Precision measurement of a brown dwarf mass in a binary system in the microlensing event," we present the precise characterization of a brown dwarf in a binary system detected during the microlensing event OGLE-2019-BLG-0033/MOA-2019-BLG-035, caused by a binary system consisting of a brown dwarf orbiting a red dwarf (Herald et al. 2022). Thanks to extensive ground-based observations and the availability of space-based observations from Spitzer, it was possible to obtain precise estimates of all microlensing parameters, including parallax, source radius, and the orbital motion of the binary lens. The precise modeling process revealed that the lens is composed of a red dwarf with a mass of M1 = 0.149 $M_{\odot}$ and a brown dwarf with a mass of M2 = 0.0463 $M_{\odot}$ at a projected separation of a = 0.585 au. The system possesses a peculiar velocity typical of ancient populations with low metallicity in the thick disk. Furthermore, it is emphasized that the telescopes of the Pico dos Dias Observatory (OPD) were also used in the observations, contributing to the achievement of these precise results.

4.5. Potential detections observed in 2024

During the years 2021 to 2024, various GM events have been observed using the OPD telescopes. Many events are still under analysis by our group and the collaboration. Table 1 shows the list of potential exoplanets and binary systems detections that have publication potential in the coming years, with data collected exclusively in 2024 using OPD telescopes.

5. Impact on exoplanet research with GM

The findings detailed in this research underscore significant progress in the field of exoplanet studies. Among the key discoveries is the identification of an Earth-mass exoplanet, designated KMT-2020-BLG-0414Lb, achieved through remote observational approaches. The gathered data challenge prevailing the-

Event	# Nights	Initial Date	Telescope	Isource
KB240450	5	2024/05/31	PE	18.96
KB240697	2	2024/04/24	BC	21.42
KB240830	2	2024/05/10	BC	18.82
KB240853	3	2024/05/10	BC	19.15
KB241303	5	2024/06/10	BC	21.88
KB241350	5	2024/07/03	PE	16.56
KB241767	1	2024/07/11	PE	23.1

Table 1. GM events observed with the OPD telescopes with potential for binary lens system detection.

ories by questioning the 'break point' in the mass ratio function, suggesting that the difficulty in detecting systems with low-mass ratios might contribute more to their perceived scarcity than their actual rarity. Another important finding is the microlensing exoplanet Gaia22dkvLb, located beyond the galactic bulge. This discovery opens up fresh possibilities for detailed characterization through RV measurements, representing a promising development.. Since Gaia22dkvLb is linked with a bright host star, thorough RV measurements can be conducted, offering insights into the planet's orbital dynamics and possibly revealing more planets within the system. The discovery of KMT-2023-BLG-1431Lb, with a mass ratio below 10, also exemplifies the advances in detecting planets with subtle observational features. Furthermore, accurate determination of a brown dwarf's mass within a binary system highlights improvements in measurement precision.

Collectively, these findings demonstrate the effectiveness of using multiple observation techniques and collaborations among observatories. They also emphasize the potential for future research to expand our understanding of exoplanet diversity and formation, particularly by combining microlensing and RV techniques to explore underrepresented areas of planetary demographics. Our contribution includes conducting observations, data reduction, and analysis, as well as active participation in modeling the detected systems. The discoveries we helped achieve not only expand our knowledge of exoplanets but also challenge existing theories and open up new research opportunities, such as the possibility of additional characterization by RV. Therefore, our involvement in the project and leadership of observations at OPD not only enriches international collaborative work but also strengthens Brazil's position as a key player in exoplanet research through GM.

6. Conclusion

This work highlights significant advances in exoplanetary research, underlining the pivotal role of telescopes at the Pico dos Dias Observatory (OPD) in each detection. The OPD telescopes have played a crucial role in obtaining groundbreaking outcomes in exoplanet research, such as the Earth-mass KMT-2020-BLG-0414Lb and the fascinating Gaia22dkvLb.. These observations demonstrate not only the adaptability of scientific methods during challenging periods such as the COVID-19 pandemic, but also the importance of international collaborations. The data obtained through OPD's telescopes have challenged previous assumptions in exoplanetary mass ratio theories, highlighting that low-mass ratio systems are more constrained by observational technology than by their absence. The ability to potentially characterize Gaia22dkvLb further through radial-velocity measurements, thanks to OPD's contributions, marks a significant progress towards understanding orbital properties and associated planetary systems.

Together with exact mass determinations of planetary systems such as KMT-2023-BLG-1431Lb, as well as studies of brown dwarfs in binary systems, we gain a deeper understanding of the dynamics involved in celestial formation. The comprehensive efforts driven by OPD have significantly enriched our grasp of the diversity of exoplanets in our galaxy. Through its active contribution, Brazil, particularly via OPD, continues to cement its position as a substantial contributor to global exoplanetary research, enhancing the scope of future astronomical discoveries.

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