High-contrast, high-angular resolution view of the GJ 367 exoplanet system

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ABSTRACT

We search for additional companions in the GJ 367 exoplanet system, and aim at better constraining its age and evolutionary status. We analyse high contrast direct imaging observations obtained with HST/NICMOS, VLT/NACO, and VLT/SPHERE. We investigate and critically discuss conflicting age indicators based on theoretical isochrones and models for Galactic dynamics. A comparison of GAIA EDR3 parallax and photometric measurements with theoretical isochrones suggest a young age ≤60 Myr for GJ 367. The star’s Galactic kinematics exclude membership to any nearby young moving group or stellar stream. Its highly eccentric Galactic orbit, however, is atypical for a young star. Age estimates considering Galactic dynamical evolution are most consistent with an age of 1 to 8 Gyr. We find no evidence for a significant mid-infrared excess in the WISE bands, suggesting the presence of a substellar companion (Kervella et al. 2022). The absence of warm dust in the GJ 367 system. The direct imaging data provide significantly improved detection limits compared to previous estimates. At 530 mas (5 au) separation, the SPHERE data achieve a 5 sigma contrast of 2.6 × 10⁻⁶. The data exclude the presence of a stellar companion at projected separations ≥0.4 au. At projected separations ≥5 au we can exclude substellar companions with a mass ≥ 1.5 M_jup for an age of 50 Myr, and ≥ 20 M_jup for an age of 5 Gyr. By applying the stellar parameters corresponding to the 50 Myr isochrone, we derive a bulk density of ρ_planet = 6.2 g/cm³ for GJ 367 b, which is 25% smaller than a previous estimate.

Key words: Planets and satellites: gaseous planets – Planets and satellites: formation – Planets and satellites: detection – Planets and satellites: dynamical evolution and stability

1 INTRODUCTION

GJ 367 is an early M-dwarf located at a distance of 9.4 pc, with a close-to-solar metallicity of [Fe/H] = −0.01 ± 0.12. It is host to GJ 367b, a transiting exoplanet with a 7.7 h orbital period, corresponding to a semi-major axis of ≈0.007 au (≈0.75 mas maximum projected separation for a circular orbit). With an estimated radius of 0.72 R_solar and mass of 0.55±0.03 M_Earth, GJ 367b is currently the smallest and lowest mass exoplanet known within 10 pc of the Sun. The implied density of 8.2 g/cm³ classifies it as a rocky planet with an extended, iron dominated core. With a dayside equilibrium temperature of 1500 to 1750 K, GJ 367b classifies as a lava planet (Lam et al. 2021).

The host star GJ 367 is showing no signs of strong variability or activity. Photometric monitoring covering 5 yr, and comprising 11 distinct observing epochs, derived a V-band variability amplitude of 12 mmag (Hosey et al. 2015). GJ 367’s activity index of RHK = −5.15±0.12 and rotational period of Protot = 53 day (Astudillo-Defru et al. 2017) closely follow the relation typical for relatively quiet early M-dwarfs (Suárez Mascareño et al. 2015). One peculiarity of GJ 367 is its high space motion with respect to the Sun. As recently as 130,000 yr ago, the Sun and GJ 367 had their closest encounter at a periHELION distance of ≈5.4 pc (Bailer-Jones et al. 2018). An analysis combining HIPPARCOS and GAIA EDR3 astrometry of GJ 367 finds a 3.8σ significance for a proper motion anomaly, possibly indicating the presence of a substellar companion (Kervella et al. 2022). The GAIA EDR3 astrometric excess noise, which is the noise to be added to the individual GAIA observations for achieving a reduced χ² of 1 in the astrometric fit of the single star model (Lindegren et al. 2018), has a significance of ≈17σ (Gaia Collaboration et al. 2016, 2021).

The proximity to the Sun, and the EDR3 astrometric anomaly make GJ 367 an interesting target for a direct imaging search for companions at projected separations ≥1 au.

The outline of the paper is as follows: In section 2 we present the high-angular resolution data and their analysis. In section 3 we investigate various age indicators and the Galactic kinematics. In section 4 we discuss the findings, and identify four challenges towards a better understanding of the GJ 367 exoplanet system.

2 OBSERVATIONS AND DATA REDUCTION

We identified three high angular and high contrast observations of GJ 367 in the Mikulski Archive for Space Telescopes and the archive of the European Southern Observatory (see Table 1).

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Table 1. Basic parameters of high contrast observations of GJ 367

| Telescope/instrument | HST/NICMOS | VLT/NACO | VLT/SPHERE |
|----------------------|------------|----------|------------|
| Camera               | NIC2       | S13      | IFS        |
| Field of view ("×") | 19.4 × 19.4| 13.6 × 13.6| 11.0 × 12.5|
| Image scale (mas/pixel) | 75.65 | 13.25 | 12.25 |
| Filter/wavelength range | F110W, F180W, F207M, F222M | F185N | YJ |
| Angular resolution (mas) | ≥95 | 48 | ≥25′ |
| Total integration time [s] | 64, 64, 128, 128 | 280 | 3136 |
| Integration set-up | STEP64, STEP128 | 0.5s × 20 × 28 | 32s × 1 × 98 |
| Telescope tracking | stare | auto-jitter | pupil stabilized |
| Programme ID | GO 7420 | 70C-0738(A) | 0104C-0336(A) |
| Principal Investigator | David A. Golimowski | Jean-Luc Beuzit | Anna Boehle |
| Observing date | 1997-09-17 | 2003-03-17 | 2020-02-08 |
| Remarks | snapshot | low wind effect | ADI + Lyot coronagraph |

*Inner working angle = 150 mas with apodized Lyot coronagraph.

Table 2. Companion candidates (cc) to GJ 367

| ID | Epoch | sep ["] | PA [deg] | ∆mag [mag] | status | GAIA EDR3 ID |
|----|-------|----------|----------|------------|--------|--------------|
| cc1 | 1997-09-17 | 8.03 | 222.2 | 11.46 (F110W) | non-common proper motion | 5412250575032741504 |
| cc2 | 1997-09-17 | 8.45 | 3.1 | 3.39 (F110W) | non-common proper motion | 5412250575040992256 |
| cc3 | 1997-09-17 | 11.54 | 18.9 | 11.95 (F110W) | background star (no CH₄ absorption) | — |
| cc4 | 1997-09-17 | 8.72 | 40.7 | 10.07 (F110W) | non-common proper motion | 5412250575040992768 |
| cc5 | 1997-09-17 | 9.05 | 51.8 | 8.44 (F110W) | non-common proper motion | 5412250540683548160 |
| cc6 | 2020-02-08 | 6.48 | 39.8 | 11.13 (H2) | background M-dwarf (H2-H3 colour) | — |

Separation “sep” and Position Angle “PA” are measured relative to GJ 367 in the epoch of the respective high-contrast observations.

Figure 1. Left: HST NIC2 image in F110W centered on GJ 367, with five companion candidates (cc) visible (black circles). The location of residuals originating in NIC2’s coronagraphic mask is indicated (white circle). Right: VLT/NACO image in NB175 centered on GJ 367. The lower left insert shows a 4x zoom-in on an individual 10s frame depicting a side-lope resulting from the low wind effect. The insert on the lower right shows a 4x zoom-in of the coadded PSF.

2.1 HST/NICMOS

GJ 367 was observed with HST/NICMOS (Thompson & Schneider 1998) as part of a snapshot survey for companions to nearby stars (see Table 1 for observational details). The filter combination had been selected to provide a differentiator between background stars and substellar companions with CH₄ absorption bands (Dieterich et al. 2012).

We detect 5 companion candidates (cc) to GJ 367 in all 4 bands of the NIC2 data set (see Figure 1, left, cc1 to cc5, and Table 2). GAIA parallax measurements and upper limits identify four of these sources as background objects. The brightest source cc2 was already classified as a background dwarf star based on its F110W - F222M
H3 colours are source has no counterpart in EDR3. Compared to GJ367, cc6’s H2 - the VLT/NACO observations have a 2 times finer diffraction-limited wind effect. The insert in the lower right shows the coadded frame. an example one of several individual frames affected by the low- with the EsoRex NACO pipeline Version 4.4.10. Figure 1 (right) sources (Milli et al. 2018; Sauvage et al. 2016). We reduced the data = 0.37 0.19 m/s). The resulting low-wind effect is known to create phase shifts in the wavefront in specific quadrants of the telescope pupil, resulting in one or multiple (transient) side-lopes of point sources (Milli et al. 2018; Sauvage et al. 2016). We reduced the data with the EsoRex NACO pipeline Version 4.4.10. Figure 1 (right) shows the coadded image. The insert on the lower left shows as an example one of several individual frames affected by the low-wind effect. The insert in the lower right shows the coadded frame. The side-lope is much less pronounced, yet still visible as a diffuse “smudge” to the upper left of the PSF center. Compared to the shortest wavelength HST/NIC2 observations, the VLT/NACO observations have a 2 times finer diffraction-limited resolution. The data confirm that GJ 367 is unresolves (i.e. not a stellar binary) down to a projected separation of ≈0.4 au (Figure 1, right). We also carried out a visual search for companion candidates. No other sources were detected down to mNB175 ≈ 13.5 mag (i.e. about 7.5 mag fainter than GJ 367), cc1, which is about 10.1 mag fainter than GJ 367 in GAIA BP and RP, and like GJ 367 has GAIA BP - RP ≈2.3 mag, is below the detection limit of the VLT/NACO data set.

2.3 VLT/SPHERE

GJ 367 was observed with VLT/SPHERE (Beuzit et al. 2019) as part of a programme to probe for substellar companions to nearby stars (see Table 1). The pupil stabilized angular differential imaging (Marois et al. 2006, ADI) observing sequence was obtained with the apodized Lyot coronagraph (Soummer et al. 2011; Cariblet et al. 2011; Martinez et al. 2009). Before the start and after the end of the coronagraphic observing sequence a single data set with the satellite spots turned on was recorded in order to facilitate the estimation of the star center position behind the coronagraph. During the ADI sequence, the satellite spots were not present.

We reduced the data using a combination of the EsoRex SPHERE pipeline version 0.42.0 and the vlt-sphere python package version 1.4.3 (Vigan 2020). For the astrometric calibration (i.e. image plate scale and orientation) we adopted the values by Maire et al. (2016).

A point source cc6 is detected (Figure 2, left, and Table 2) in the IRDIS H2 (λc = 1589 nm) and H3 (λc = 1667 nm) bands. This source has no counterpart in EDR3. Compared to GJ 367, cc6’s H2-H3 colours are ≈ 0.1 mag redder. Thus most likely it is a background star of slightly later spectral type than GJ 367. Due to the high proper motion of GJ 367, there is no overlap between the field of view of NIC2 in 1997 and IRDIS in 2020.

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Table 3. Compilation of (apparent) optical, near-, and mid-infrared photometry, distance modulus (DM), and absolute flux (i.e. at 10 pc distance) of GJ 367

| Band | [mag] | IFλ (10⁻¹² W/m²) | Source |
|------|-------|-------------------|--------|
| GBP  | 10.3735±0.0008 | 1.346±0.0002 | EDR3   |
| G    | 9.1587±0.0003 | 3.069±0.0002 | EDR3   |
| GRIp | 8.0582±0.0005 | 4.959±0.0003 | EDR3   |
| J    | 6.632±0.023  | 7.635±0.007  | 2MASS  |
| H    | 6.045±0.044  | 6.26±0.13     | 2MASS  |
| KS   | 5.780±0.020  | 4.00±0.17    | 2MASS  |
| W1   | 5.550±0.164  | 1.459±0.027  | AllWISE|
| W2   | 5.364±0.061  | 0.71±0.12    | AllWISE|
| W3   | 5.477±0.015  | 0.045±0.003  | AllWISE|
| W4   | 5.381±0.038  | 0.0071±0.0001| AllWISE|
| DM   | -0.1300+9.9568-0.0029 | — | EDR3   |

References: EDR3 - Gaia Collaboration et al. (2021); 2MASS - Cutri et al. (2003); AllWISE - Cutri et al. (2021)

Table 4. Compilation of metallicity estimates of GJ 367

| [Fe/H] | Reference  |
|--------|-----------|
| -0.07±0.09 | Kuznetsov et al. (2019) |
| -0.06±0.09 | Maldonado et al. (2019) |
| -0.01±0.12 | Lam et al. (2021) |

The resulting pre-reduced 4D (x,y,time,wavelength) IRDIS and IFS data sets were further processed with ANDROMEDA version 3.1 (Cantalloube et al. 2015). Figure 2 (right) shows the resulting residual after spectral ADI (SADI) processing of the IRDIS data. No close companion candidate was detected. Figure 3 shows the radial contrast curve (red dashed line) for our SADI analysis of the SPHERE/IRDIS dual band imaging data. In the central 700 mas (=6.6 au projected separation), IFS and IRDIS contrast curves after SADI processing are quite similar. VLT/SPHERE achieves a 5σ contrast of ≈ 2.6 × 10⁻⁶ at 5 au (520 mas), and ≈ 1 × 10⁻⁶ beyond 14 au (1500 mas). The HST/NIC2 contrast curve (black dotted line) according to Dieterich et al. (2012) is overplotted for reference.

3 AGE AND FORMATION HISTORY OF GJ 367

The age determination presents the main challenge in converting the contrast ratio between a substellar companion and its host star into a mass estimate. Primary age indicators are the evolutionary state of the star, its activity and rotational period, and Galactic kinematics (Soderblom 2010).

3.1 Isochronal age and metallicity

The proximity of GJ 367 results in precise parallax measurements, and hence a precise determination of its absolute magnitudes. Table 3 presents a compilation of optical and infrared photometry of GJ 367. Its metallicity is close to solar (Lam et al. 2021), which makes theoretical isochrones computed for solar metallicity directly applicable (see Table 4 for a compilation of recent metallicity estimates). In Figure 4, left, we compare GJ 367’s absolute GAIA BP magnitude and GAIA BP - RP colour with theoretical isochrones by Baraffe et al. (2015). Under the assumption that GJ 367 is a single star, the isochrones suggest an age of around 55 to 60 Myr. Isochrones in the 2MASS photometric system, on the other hand, do not provide an
age discriminant. This is in part due to the larger photometric uncertainties of the 2MASS measurements, and in part due to the fact that the isochrones in the 2MASS system are degenerate\(^2\) for objects of GJ 367’s near infrared colours and magnitudes (Figure 4, right).

\(^2\) As pointed out by Allard & Hauschildt (1995), for late-type dwarfs of solar metallicity, molecular opacities lock in place the peak of the flux at \(\approx 1.1\) \(\mu\)m over a broad range of effective temperatures. Thus the flux in the visual provides a better diagnostics on effective temperature and evolutionary state.

Thus we consider the isochronal age estimate of \(8.0^{1.3}_{-0.8} \) Gyr by Lam et al. (2021), which is based on the GAIA DR2 parallax and the 2MASS photometry, of limited informative value.

A comparison of GJ 367’s location in a GAIA colour-magnitude diagram with the other \(\approx 150\) M dwarfs within 10 pc of the Sun (using the sample defined by Stelzer et al. 2013) reveals that its colour and magnitude is rather typical (i.e. average) for an early M-dwarf (Figure 4, left). The dispersion in absolute magnitudes above the (solar metallicity) main sequence for nearby late K- and early M-type stars can in part be explained by unresolved binary stars (Zari et al. 2018), and in part by a spread in metallicity above solar.

By being about 0.5 mag brighter in the optical and near infrared than the 1 to 10 Gyr solar-metallicity main-sequence, GJ 367’s location in the colour magnitude diagram coincides with the binary sequence. Our direct imaging data exclude a stellar companion at projected separations \(\approx 0.4\) au in the 2003 data set, and at projected separations \(\approx 1\) au in the data sets obtained in 1997 and 2020. We also found no evidence in the literature for GJ367 having a closer-in stellar companion (i.e. no hint for a spectroscopic, astrometric, or eclipsing binary).

In order to investigate the effect of the uncertainty in the metallicity of GJ 367 (Table 4) on the isochronal age estimate, we use the Mesa Isochrones and Stellar Tracks (MIST, Dotter 2016) in the GAIA EDR3 photometric system and for [Fe/H] = (-0.25, 0.00, +0.25). To account for the long rotational period of GJ 367, we selected the isochrones for \(\nu/\nu_{\text{crit}}=0.0\). For [Fe/H] = 0.0 \(\pm\) 0.25, we derive an isochronal age of \(28^{17}_{-19}\) Myr for GJ 367. In general, sub-solar metallicity isochrones suggest a younger age, and super-solar metallicity isochrones yield an older age.

According to the MIST models, a 1 to 10 Gyr old early M-dwarf with a metallicity of [Fe/H] \(\approx +0.45\) would fit GJ 367’s optical and near infrared luminosity. Such a high metallicity, though, deviates by at least 4 \(\sigma\) from GJ 367’s close-to-solar metallicity estimates.
3.2 Mid-infrared emission

Bentley et al. (2019) investigated GAIA, 2MASS, and WISE photometry of ≈100,000 nearby M-dwarfs. With G = 2.53 mag, and G-K = 3.38 mag, GJ 367’s GAIA and 2MASS colours are typical for M1 to M2 dwarfs. Compared to early M-dwarfs in the ≥500 Myr old field star sample, though, GJ 367’s reveals a 2 to 3 \( \sigma \) infrared excess in the WISE bands (K-W2 = 0.42 mag, W1-W2=0.19 mag, see Table 3). We also compare the spectral energy distribution of GJ 367 with models for a 0.4 M\(_\odot\) star by Baraffe et al. (2015). According to the models, the 0.4 M\(_\odot\) star has \( T_{\text{eff}} = 3512 \) K at an age of 50 Myr, and \( T_{\text{eff}} = 3521 \) K at an age of 5 Gyr, which is a very good match to the \( T_{\text{eff}} = 3522\pm70 \) K reported by Lam et al. (2021). While the 50 Myr model provides a good fit to the photometry of GJ 367, the 5 Gyr model predicts only about 65\% to 70\% of its observed optical, near- and mid-infrared flux.

3.3 Gyrochronology and age

Gyrochronology relies on the assumption that young stars at the end of their contraction phase arrive on the main-sequence with a high-angular momentum, and subsequently are able to lose angular momentum by stellar winds. Main-sequence stars with longer rotational periods should thus be on average older than main sequence stars with shorter rotational period. This then facilitates age-dating by comparing the rotational period of P\(_{\text{rot}}\), with the theoretical models for a 0.4 M\(_\odot\) star from its rotational period (Mamajek 2012). Single Hyades members from the sample defined by Kopytova et al. (2016) with masses of \( \approx 0.4 \) M\(_\odot\) have a typical rotational period of \( \approx 20 \) days, which is about 3 times longer than predicted by models of the angular momentum evolution of low mass stars (Reiners & Mohanty 2012). According to Douglas et al. (2016) this suggests that for single stars with undisturbed circumstellar disks, magnetic braking might be a highly efficient mechanism to shed angular momentum. As a consequence the rotational period of early M-dwarfs might have less informative power as an age indicator.

### Table 5. GJ 367’s Galactic coordinates and velocities in a left-handed coordinate system (not corrected for LSR)

| XYZ [pc] | UVW [km/s] |
|----------|------------|
| 0.3667, -9.3621, 0.9289 | -3.27, -50.87, -28.30 |

Note: Based on positions, parallax and proper motions from GAIA EDR3, radial velocity according to Trifonov et al. (2020), and the transformation matrix defined in ESA (1997).

3.4 Galactic kinematics and moving groups membership

We base our investigation of GJ 367’s Galactic kinematics on GAIA EDR3 positions, parallax and proper motions, and on the weighted mean radial velocity of RV = 47.9216±0.0001 km/s from the public HARPS data base corrected for systematics (Trifonov et al. 2020). The transformation from the GAIA EDR3 observables in the International Celestial Reference System (ICRS) to XYZ positions and UVW velocities (see Table 5) in a left-handed Galactic reference frame (U positive for motions towards the Galactic anti-center) is based on the transformation matrix defined in ESA (1997). The resulting values are U = -3.3 km/s, V = -50.9 km/s, and W = -28.3 km/s. This is in very good agreement with Lam et al. (2021) (U\(_{\text{LSR}},\) V\(_{\text{LSR}},\) W\(_{\text{LSR}}\) = (-11.73 ± 0.01, -36.5 ± 0.4, -21.93 ± 0.04)), when assuming that they based their correction to the local standard of rest (LSR) on Coşkunoğlu et al. (2011), i.e. U\(_\odot\), V\(_\odot\), W\(_\odot\) = (-8.50, 13.38, 6.49) km/s in a left-handed coordinate system (thus the minus sign in U\(_\odot\)).

We note that Lam et al. (2021)’s choice of LSR correction results in a small inconsistency when they assess the likelihood for GJ 367’s membership to the different Galactic populations according to Bensby et al. (2003). The latter report U\(_{\text{LSR}},\) V\(_{\text{LSR}},\) W\(_{\text{LSR}}\) for thin and thick disk, and halo stars in a right-handed coordinate system, and based on a solar motion with respect to 

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**Figure 4.** Colour-magnitude diagrams for GJ 367 compared of theoretical models by Baraffe et al. (2015). The plot on the left shows isochrones in the GAIA photometric systems, with GJ 367 (red symbol) being located below the 50 Myr and above the 80 Myr isochrone. The plot on the right illustrates that isochrones transformed to 2MASS bands do not provide any meaningful constraint on GJ 367’s age. The 1 \( \sigma \) error bars in both plots are based on the uncertainties in photometry and parallax.
Figure 5 illustrates that GJ 367’s kinematics differ significantly from those of nearby young moving groups (Malo et al. 2013), and hence excludes membership to any of these groups. GJ 367’s UVW velocities are also distinct from those of the Hercules stream (see, e.g. Chen et al. 2021). This finding is supported by the LACeWINg (Riedel et al. 2017) and BANYAN (Gagné et al. 2018) analysis tools for assessing membership to nearby young moving groups. Thus GJ 367 is not a member of any nearby moving group or stream.

3.5 Age constraints from Galactic dynamics

The birth conditions and subsequent evolutionary history of stellar populations determine their present-day Galactic kinematics and metallicity. Frankel et al. (2018, 2020) constructed a global model for the distribution of stars’ [Fe/H], ages, positions and velocities, and fitted it to APOGEE DR12 and DR14 data. Here, we use this model to produce an age posterior for the star, given its [Fe/H] and kinematics.

Noteworthy are GJ 367’s V and W components, i.e., the velocity component parallel to the Galactic plane and perpendicular with respect to the Galactic center, and the velocity component vertical to the Galactic plane. Relative to the Sun, GJ 367’s V component is ≈50 km/s less, and thus considerably slower than the circular velocity at the position of the Sun. This indicates a Galactic orbit with a significant eccentricity.

We used galpy v1.7.1 (Bovy 2015) to integrate GJ 367’s orbit with
We aim at a qualitative analysis. Quantitative estimates will vary according to the precise choice of the LSR correction.

Figure 7. Posterior age of GJ 367 based on [Fe/H], Galactic angular momentum, radial action, and height above the Galactic plane (thick black). Contributions from individual model components entering in the posterior are re-normalized and over-plotted according to the legend: star formation history and radial surface density, chemical information, orbital heating.

Table 6. Age estimators for GJ 367

| method                     | age [Myr] | reference |
|----------------------------|-----------|-----------|
| Isochrones: BHAC$^{a}$     | 57$^{+3}_{-3}$ | this paper |
| Isochrones: MESA$^{b}$     | 28$^{+3}_{-3}$ | this paper |
| Gyrochronology             | 3980 ± 1110 | Lam et al. (2021) |
| Galactic Dynamics$^{c}$    | 5500$^{+500}_{-4500}$ | this paper |

$^{a}$ assuming solar metallicity for GJ 367; $^{b}$ assuming −0.25 ≤[Fe/H]≤ +0.25 for GJ 367; $^{c}$ assuming that GJ 367’s space motion is the result of many low momentum exchange encounters, and not dominated by a single, high momentum exchange n-body interaction. Note: given the spread of age estimates, we decided to choose 50 Myr and 5 Gyr as exemplary ages for the conversion of contrast limits into mass limits.

4 DISCUSSION

The VLT/SPHERE observations provide significantly improved detection limits compared to previous direct imaging observations of the GJ 367 system. The corresponding companion mass detection limits according to models by Baraffe et al. (2003) for ages of 50 Myr and 5 Gyr are shown in Figure 8. The presence of a massive brown dwarf companion is excluded even for relatively old system ages. For a young system age, the observations would have been sufficiently sensitive to detect a 1.5 M$_{Jup}$ planet at a projected separation of 5 au. This could help to narrow down the parameter range of possible companion masses and separations calculated by Kervella et al. (2022).

According to their study, the HIPPARCOS - GAIA EDR3 proper motion anomaly would require a companion with a mass ≥1.5 M$_{Jup}$ orbiting with a semimajor axis ≥10 au, or a companion with a mass ≥1.3 M$_{Jup}$ orbiting with a semimajor axis ≤5 au (see Figure 8).

The exoplanet host GJ 367 provides contradicting age indicators (Table 6). Its intrinsic over-luminosity compared to 1 to 10 Gyr old early M-dwarfs of solar metallicity suggests a maximum age of 60 Myr.

Direct imaging observations rule out blending with a background star, or a stellar companion in a wider (≥2 au) orbit. Radial velocity monitoring also rules out a closer-in stellar companion as an explanation for the over-luminosity. Metallicity measurements rule out the high metallicity of [Fe/H] = +0.45 required according to the MIST models for a 1 to 10 Gyr old early M-dwarf to match GJ 367’s GAIA EDR3 parallax and photometric measurements.

GJ 367’s Galactic kinematics, and in particular the eccentricity of its Galactic orbit are well explained by Galactic dynamical evolution over a time period of 1 to 8 Gyr. Such an age is in agreement with the gyrochronological age, but in conflict with the isochronal age. Future studies of the [α/Fe] abundance of GJ 367 might provide more stringent constraints on its membership to a particular Galactic stellar population.

An alternative explanation for the eccentricity of GJ 367’s Galactic orbit would be a fairly recent high-energy gravitational encounter, which changed its Galactic orbital parameters. This encounter could have happened early in the youth of GJ 367, and would point to its formation in a non-hierarchical multiple system, or a relatively dense cluster environment. While we cannot distinguish between these two scenarios, there is a high probability that either event would have significantly disturbed the orbits of any potential companions to GJ 367. This would be one explanation for GJ 367 lacking companions in...
wide orbits. In general, the formation environment leaves an imprint on the architecture of planetary systems (Winter et al. 2020).

In the following we identify four challenges. Their solution might provide a better understanding of the age and evolutionary history and status of the GJ 367 exoplanet system.

- Challenge 1: can GJ 367 be overluminous, and not be young?
- Challenge 2: can magnetic braking explain the long rotational period of 50 days for an early M dwarf with an age \( \leq 60 \) Myr?
- Challenge 3: does the integration of GJ 367’s Galactic orbit back in time by 60 Myr hint at a possible birth place in a non-hierarchical multiple system, or a relatively dense stellar cluster?
- Challenge 4: does the EDR3 astrometric excess noise hint at the presence of another substellar objects in the GJ 367 system? Or is the astrometric excess noise related to the limitation of the single star linear astrometric fit in EDR3, and GJ 367’s proximity and peculiar space motion with respect to the Sun?\textsuperscript{5}

Significantly deeper direct imaging detection limits might have to wait for the next generation of telescopes and instruments. Contrast ratios of a few times \( 10^{-9} \) as envisioned for the Roman Space Telescope and its Coronagraph Instrument (Trauger et al. 2016; Kasdin et al. 2020; Carrión-González et al. 2021) could push detection limits to sub-Saturn mass planets.\textsuperscript{6}

An application of the stellar parameters according to the models by Baraffe et al. (2015) (BHAC) for an age of 50 Myr changes the dependent properties of GJ 367 b. The best fitting stellar model has a mass of 0.4 \( M_\odot \), \( T_{\text{eff}} = 3512 \) K, and \( r_{\text{star}} = 0.479 \) \( R_\odot \). While the effective temperature agrees very well with the value determined by Lam et al. (2021), the models describe a star with a 5% larger radius, and a 10% lower mass. An increase in the planetary radius from 0.72 to 0.75 \( R_{\text{Earth}} \), and a decrease in the planetary mass from 0.55 to 0.48 \( M_{\text{Earth}} \) would result in a \( \approx 25\% \) decrease in the bulk density to \( \rho_{\text{planet}} = 6.2g/cm^3 \) for GJ 367 b.

Irrespective of its age, GJ 367 b is a benchmark rocky planet in the solar neighbourhood. While the semimajor axis of \( \approx 0.007 \) au of GJ 367 b is too close to its host star for direct imaging observations, phase curve and primary and secondary transit measurements should provide interesting insights into its day- and nightside properties. At a young age, the entire surface of GJ 367 b might still be covered by lava, while at an older age the nightside might have cooled below the melting point. Thus the day- to nightside temperature contrast of GJ 367 b could serve as another age indicator for the system. At a young age, GJ 367 b could also serve as a template to Earth’s Hadean period (Bonati et al. 2019).

**Figure 8.** Radial mass detection limits for SPHERE, transformed from 5 \( \sigma \) contrast limits using the models by Baraffe et al. (2003) for ages of 50 Myr (blue dashed line) and 5 Gyr (red dashed-dotted line). The asterisk symbols and the dotted line mark the companion mass to orbital radius relation explaining the proper motion anomaly of GJ 367 according to Kervella et al. (2022).

\textsuperscript{5} After correcting for the projection of linear proper motion onto the celestial sphere, Brandt (2021) finds a good agreement between GJ 367’s proper motion derived from GAIA EDR3 and HIPPARCOS positions, and the GAIA EDR3 proper motion.

\textsuperscript{6} GJ 367 might be on the faint side of stars accessible by the Roman Coronagraph Instrument.

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**DATA AVAILABILITY**

The data underlying this article are available online from the Barbara A. Mikulski Archive for Space Telescopes and the archive of the European Southern Observatory. The final data products are made available by contacting the corresponding author.
