

The origins of the substellar companion to GQ Lupi

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ABSTRACT

The recently discovered substellar companion to GQ Lup possibly represents a direct test of current planet formation theories. We examine the possible formation scenarios for the companion to GQ Lup assuming it is a $\sim 2 M_{\text{Jup}}$ object. We determine that GQ Lup B most likely was scattered into a large, eccentric orbit by an interaction with another planet in the inner system. If this is the case, several directly observable predictions can be made, including the presence of a more massive, secondary companion that could be detected through astrometry, radial velocity measurements, or sculpting in GQ Lup's circumstellar disk. This scenario requires a highly eccentric orbit for the companion already detected. These predictions can be tested within the next decade or so. Additionally, we look at scenarios of formation if the companion is a brown dwarf. One possible formation scenario may involve an interaction between a brown dwarf binary and GQ Lup. We look for evidence of any brown dwarfs that have been ejected from the GQ Lup system by searching the 2MASS all-sky survey.

Key words. stars: individual: GQ Lup – planets and satellites: formation – stars: low-mass, brown dwarfs

1. Introduction

The recent discovery of a substellar companion to GQ Lup has started an exciting phase of extrasolar planet studies, where direct images of planetary companions can inform substellar spectral models as well as models of planet formation. The inferred age and distance to the companion, as well as its absolute photometry, is consistent with a lower limit of $\sim 2 M_{\text{Jup}}$ (Neuhäuser et al. 2005). The models that were used to determine the lower limit are based on those of Wuchterl & Tscharnuter (2003).

GQ Lup itself is a $0.7 M_{\odot}$ star with an age of ~ 1 Myr at a distance of 140 pc within the Lupus 1 cloud (Neuhäuser et al. 2005; Tachihara et al. 1996; Wichmann et al. 1998; Knude & Hog 1998). Since GQ Lup is a young star, it still possesses an unresolved circumstellar disk that nevertheless shows up as a strong mid- and far-infrared excess (Hughes et al. 1994; Weintraub 1990). GQ Lup resides in a relatively isolated star forming region within the Lupus complex of clouds, a string of four dark clouds that holds several small young stellar associations (Hughes et al. 1994).

The companion, or GQ Lup B, was observed at a projected separation of $0.7''$ from its host star and has had its common proper motion confirmed. At a distance of 140 pc, the projected separation is 98 AU. It has absolute K_s and L' magnitudes of 13.1 and 11.7, corresponding to a luminosity of $\sim 10^{-2} L_{\odot}$ (Neuhäuser et al. 2005). Additionally, low resolution spectra of the companion identify it as a $\sim L1$ type object with a T_{eff} of ~ 2000 K. Based on GQ Lup B's spectral type, low specific

gravity, and infrared photometry, Neuhäuser et al. (2005) concluded that GQ Lup B is most likely a planetary object.

The large separation between GQ Lup and its companion provides a unique test for the formation of planetary systems, since this system does not resemble the Solar System or indeed any of the other known extrasolar planetary systems. GQ Lup B's origin can provide useful insights into how giant planets form. In this paper, we endeavor to sketch out the possible origin of GQ Lup B and to determine observational signatures that test whether this formation scenario is correct. In Sect. 2 we determine the most likely scenario for the formation of GQ Lup B, while in Sect. 3 we determine the observational signatures of this scenario. Finally in Sect. 5 we present our conclusions.

2. Planet formation scenarios

2.1. *In situ* formation

It is unlikely that GQ Lup B formed in its current location given its extremely large projected separation from GQ Lup. Core accretion is the generally accepted method of forming a planet like Jupiter (Safronov 1969). Core accretion formation times scale roughly as $t_{\text{form}} \propto a^2$, where a is the object's semi-major axis (Pollack et al. 1996; Safronov 1969). This also assumes a surface density of the protoplanetary disk that decreases as $R^{-3/2}$. If it takes ~ 1 Myr to form an object like Jupiter at 5 AU, it will take 400 times longer than the lifetime of GQ Lup to form an object at GQ Lup B's orbital separation. Also, such formation requires many orbital periods. Assuming a circular

orbit with a semi-major axis equal to the projected separation, GQ Lup B has had $\sim 10^3$ orbital periods in the entire lifetime of the star, whereas Jupiter required roughly 10^5 orbital periods to form in the core accretion scenario.

Another possibility is that this planet formed by direct collapse of the gaseous material in the disk (Cameron 1978; Boss 1997). Such a collapse generally takes several hundred orbital periods and requires a relatively large gaseous protoplanetary disk, since the disk must be gravitationally unstable. Instability is roughly based on marginal Toomre Q values, where $Q = c_s \Omega / \pi G \sigma$ where c_s is the sound speed, Ω is the rotation rate of the gas, and σ is the surface density of the disk. Disks tend to be stable at close radii, and as the disk gets cooler, becomes unstable at greater distances. While this is the case, detailed simulations of marginally stable disks cannot produce planetary companions at ~ 100 AU because non-axisymmetric structure in the form of spiral waves transport mass interior to large separations before a planet can form (Boss 2006). These simulations also show that the spiral structure often does not overlap as is the case at smaller separations which enhances the formation of planet forming clumps.

Since in situ formation is unlikely for a planet at such a large orbital separation, some mechanism of migration must be invoked for a plausible origin to GQ Lup B. In the next sections we look at various ways of forming a Jovian planet closer to the central star and then moving it to its final position.

2.2. Stellar encounters

A close encounter between a young star with a protoplanetary disk and another star can have direct effects on the orbital parameters of planets and on the morphology of the surrounding disk. Such encounters have been used as an explanation for the ring-like structure seen in the β Pictoris disk as well as the truncation of the Solar System's Kuiper belt (Kalas et al. 2000; Larwood & Kalas 2001; Ida et al. 2000).

The close passage of a star will give a gravitational kick to any planets in orbit and potentially pump up their eccentricities. If we assume that a $\sim 2 M_{\text{Jup}}$ object formed at a distance of ~ 10 AU, we can infer the magnitude of the object's eccentricity based on its current location. If such an object received a gravitational kick, its periastron would be roughly its primordial semi-major axis assuming it was initially in a circular or close to circular orbit. After the kick the new orbit of the object would be highly eccentric, and its current position would correspond to apastron. Ignoring projection effects, the planet's orbital eccentricity would be ~ 0.8 and its orbital semi-major axis would be 54 AU.

A star's passage must be close to effect such a large eccentricity boost. If we assume the kick is impulsive, the star has to pass within two times the semi-major axis to produce an eccentricity ~ 0.8 . One can calculate how frequent such a passage would be. We assume the cross section radius to be ~ 20 AU, corresponding to a close approach capable of pumping the eccentricity to ~ 0.8 and a relative velocity of $\sim 3 \text{ km s}^{-1}$. Given these parameters, one would need a stellar number density of $\sim 10^6 \text{ pc}^{-3}$ to attain a rate of one encounter per Myr for

stars in the Lupus 1 cloud. This density is orders of magnitude larger than the typical densities of T associations, which are loosely bound groupings of stars that number in the hundreds. Assuming a density of closer to 10^3 pc^{-3} , the probability of such a close encounter occurring in 1 Myr is 10^{-3} .

2.3. Orbital migration

Torques between a circumstellar disk and a young planet often cause inward orbital migration of the planet towards its host star (Nelson & Papaloizou 2004). However, in many stellar systems, the circumstellar disk is also photoevaporated over time, either by the central star or by outside sources. In these cases, the disk is removed by a wind which corresponds to a time varying surface density in the disk. For mass loss rates an order of magnitude less than those observed in the Orion nebula, significant outward migration of planets can occur (Veras & Armitage 2004).

In the case of GQ Lup, this mechanism is not plausible for several reasons. Firstly, the mechanism of mass loss in the case of GQ Lup requires external irradiating O or B stars not currently found in the rather isolated Lupus cloud. Secondly, this mechanism cannot export the planet to orbital separations of ~ 100 AU within 1 Myr. Finally, such a mechanism would require the presence of a disk extending out to roughly the same orbital radius, which would have a high mass loss rate but still remain to both form the planet and move it outwards from an initial birthplace of ~ 10 AU. Another plausible mechanism for the truncation of the disk could again come from a stellar encounter, this time with an encounter distance of a few hundred AU. Assuming a truncation event at ~ 200 AU, the probability of that happening over 1 Myr in a 10^3 pc^{-3} T association is $\sim 10^{-2}$. It is unclear if such a truncation would propel a planet out to the very edge of the disk in a time shorter than 1 Myr.

2.4. Planet-planet scattering

The scenario of planet-planet scattering is the most convincing origin for a widely separated planet. We predict that in the GQ Lup system its planetary companion was formed in the inner system and was scattered into an eccentric orbit through interactions with at least one more massive planet (see also Boss 2006). Two jovian mass planets can become unstable to close approaches and can scatter into configurations where one planet is kicked into a highly eccentric orbit (Weidenschilling & Marzari 1996; Ford et al. 2001). Moreover, this process can mirror the observed eccentricity distribution of the known planetary systems discovered by radial velocity surveys if the planets have unequal masses that follow an M^{-1} mass distribution (Ford et al. 2003). Planet-planet interactions can cause outward orbital migration, leaving planets in wide, eccentric orbits (Marzari & Weidenschilling 2002; Veras & Armitage 2004). Furthermore, evidence for such interactions in currently known extrasolar planetary systems points to a common occurrence of interactions among protoplanetary systems (Ford et al. 2005).

Given the numerical results presented to date, one can estimate the current orbital parameters of the planets. Such

estimates will be useful for testing the ultimate origin of GQ Lup B by providing directly observable tests for this scenario. Given that the region for the formation of giant planets seems to be $\sim 5\text{--}10$ AU, we will assume that GQ Lup B formed in this region and was kicked out to its present orbit by a currently unseen inner companion that remained in this general region. Once again, we can estimate the outer planet's final eccentricity based on its current projected separation and this assumed initial semi-major axis and derive an $e \sim 0.8\text{--}0.9$. Inspection of the various cumulative distribution functions of Ford et al. (2001) and Veras & Armitage (2004) demonstrate that such large eccentricities are possible, depending on the mass ratio of the planets to the star and the ratio of the two planetary masses. Furthermore, the percentage of systems that result in a wide, eccentric orbit is on the order of a few percent. If each star in the Lupus cloud has suffered one scattering event in 1 Myr, then it is likely that one system in the cloud would have a widely separated companion like GQ Lup B.

The inner planet is likely a more massive planet than GQ Lup B itself, given that lower mass objects are often pumped to large distances in two body encounters. Given the M^{-1} probability distribution of masses, and picking between $2\text{--}12 M_{\text{Jup}}$, one would expect the second planet to have a 68% chance of being between $2\text{--}7 M_{\text{Jup}}$. Its orbital semi-major axis should be smaller but close to the initial semi-major axis within a factor of two. Its eccentricity, assuming it does not suffer from orbital migration through interaction with a circumstellar disk, should be >0.1 (Ford et al. 2001; Veras & Armitage 2004).

Another possibility is that this is a system in the process of ejecting one of its planets. Given the young age of the star, the first unstable interaction between the two objects would have occurred toward the latter stages of the formation timescale. Since this timescale is most likely on the order of 1 Myr, the first kick probably occurred within the last 10^5 yr. The current orbital timescale of GQ Lup is ~ 500 yr assuming a semi-major axis of 54 AU (corresponding to an orbit with $e = 0.8$). This corresponds to ~ 200 orbital periods of the outer planet. Since ejections of planets can happen slowly over several conjunctions between two planets, if one or both orbital solutions for the companions to GQ Lup are known, one can predict the likelihood of ejection.

Finally, this scenario is not limited to the interaction of two planets (Marzari & Weidenschilling 2002). A similar scenario would play out with multiple planets, though the orbits of the other planets would be harder to predict.

3. Observational implications of each scenario

While many of the proposed scenarios are implausible, each has their own observational consequences, which in combination with plausibility will allow a choice between the possible formation pathways. In situ formation and outward migration through interaction with a disk will result in a circular orbit for GQ Lup B. Stellar interaction would leave GQ Lup B in a highly eccentric orbit, as would planet-planet interactions. Planet-planet interactions require at least one more planet that is more massive and in an orbit consistent with a recent interaction present in the inner system. Since

planet-planet interactions require the presence of a second, more massive planet in closer orbit around GQ Lup, the quickest direct test of all of these scenarios is to study GQ Lup for radial velocity or astrometric variations. Given our possible range of masses and semi-major axes for the second companion, we will look at two benchmark cases which represent the best and the worst possible cases. The best case would be a $7 M_{\text{Jup}}$ object in a 2.5 AU orbit, which we denote as Case 1, the worst case a $2 M_{\text{Jup}}$ object in a 10 AU orbit, which we denote as Case 2.

For astrometric observations, the increase in mass is offset by a decrease in orbital semi-major axis and one expects ~ 0.2 mas amplitudes for both cases in orbital motion, excellent for SIM or high precision differential astrometry from the ground (Ford & Tremaine 2003; Lane & Muterspaugh 2004). The big difference will be the timescale for these measurements, since the orbit of Case 1 will have a period of ~ 5 yr, and Case 2's orbit will have a period of ~ 40 yr. For radial velocity measurements, both objects should be detectable within several years, either as a positive velocity trend or a full orbit, depending on where the object is between Case 1 and Case 2. For Case 1, we would expect a velocity amplitude (assuming circular orbits) close to 160 m s^{-1} , and for Case 2 the amplitude would be closer to 22 m s^{-1} . Neuhäuser et al. (2005) have monitored this object since 1999, so part of the parameter space spanned by Case 1 and Case 2 will be directly tested within a few years. Of concern is the fact that GQ Lup is a young star, and has a higher intrinsic radial velocity scatter. The scatter in m/s can be estimated based on the amount of photometric variability a star has. For GQ Lup, its variability would be estimated to be $\sim 6.5(0.4\delta V)^{0.9} v \sin i$ m/s (Saar & Donahue 1997). GQ Lup is variable, with an amplitude of $\Delta V \sim 0.34$, corresponding to a characteristic scatter in radial velocity of $\sim 74 v \sin i$ m/s. It may be difficult to detect a planetary companion with this intrinsic radial velocity scatter, though the orbital timescale of the companion is much larger than the timescale of GQ Lup's variability.

There are also several secondary and more indirect ways of inferring the presence of a second companion close to the star. An SED of GQ Lup's circumstellar disk could show the presence of a gap or hole caused by the more massive second companion. IRAS and 2MASS data have already been taken, and when combined with *Spitzer* photometry or spectroscopy, could show the presence or absence of gaps or a clearing in the center of GQ Lup's circumstellar disk.

4. Brown dwarf formation scenarios

Since the upper mass limit of GQ Lup B would make it a brown dwarf, it is an interesting test of brown dwarf formation as well and adds to the paucity of known brown dwarf companions to stars. Many of the postulated explanations for the formation of brown dwarfs are primarily interested in unbound objects or those in brown dwarf-brown dwarf binaries. The canonical example of brown dwarf companion formation is a kind of stalled fragmentation where small cores form in the disks of larger primary stars or in star forming filaments and are weaned from their accretionary clouds by being ejected from their natal source of material (Reipurth & Clarke 2001). For this

scenario to work, GQ Lup itself must retain the amount of material it needs to become a $0.75 M_{\odot}$ star, while little material remains for its companion at a separation of 100 AU. Disk collapse with competitive accretion seems to create brown dwarf-like companions, though the high mass ratio of GQ Lup to a brown dwarf is not seen in hydrodynamical simulations made to date (Bate & Bonnell 2005). Furthermore, formation models of gravitationally unstable disks suggest that brown dwarfs can form through disk fragmentation at only orbital periods $\gtrsim 2 \times 10^4$ yr, which is much further than the projected separation of GQ Lup B (Matzner & Levin 2005). If this is true, the brown dwarf had to migrate inwards on a timescale of $\ll 1$ Myr.

Capture of a brown dwarf companion is about as rare (if not moreso) than the frequency of close encounters with other stars calculated in Sect. 2.2, and therefore most likely not important. Similarly, GQ Lup B would not be the remnant of a photoevaporated stellar core since no high mass stars are present in this star forming region. Another idea for brown dwarf formation is the dissolution of brown dwarfs formed in unstable orbits around binary stars (Jiang et al. 2004). GQ Lup does not appear to have a binary stellar companion, so this scenario is also ruled out.

The general argument against brown dwarf companions relies on the fact that any low mass companion to a protostar will continue to accrete from a circumbinary disk until its mass is comparable to the primary (Jiang et al. 2004). This scenario requires a disk to remain present, but in a small number of cases, the circumbinary disk could be truncated through interactions with other stars in the star forming region.

For GQ Lup, this would require a truncation far in excess of 100 AU since it is not a dense cluster, coupled with the possible limitation to disk fragmentation at large orbital separations. This process should also form brown dwarf/brown dwarf+star triple systems that are loosely bound. In a situation similar to that described by Jiang et al. (2004), the triple could be unstable on short timescales and dissolve, leaving an ejected brown dwarf and a brown dwarf/star binary with a smaller semi-major axis than where the brown dwarfs initially formed. Given the low frequency of brown dwarf companions to stars this process need not be terribly efficient, just efficient enough to produce the observed systems.

In this case, a directly observable consequence occurs in the form of another brown dwarf object within a distance $\sim \tau_{ej} v_{esc}$, where τ_{ej} is the timescale since the ejection of the the third brown dwarf, and v_{esc} is the escape velocity of the brown dwarf. The brown dwarf should be less massive than GQ Lup B. The timescale for ejection must be less than the age of the system, or 1 Myr, and we assume a maximum v_{esc} of 1 km s^{-1} corresponding to an ejection at an orbital separation of ~ 800 AU, the maximum distance from GQ Lup would be roughly 1 pc or 0.5° at a distance of 140 pc. Any brown dwarf within this distance would be an ejection candidate. *Spitzer* IRAC mapping of this region would be fairly straightforward, since a sensitivity of ~ 1 mJy would be required for each image based on the mid infrared photometry of GQ Lup B. Since the field of view for IRAC is $5' \times 5'$, a map of the entire region surrounding GQ Lup B could be done for all 4 IRAC filters in roughly 1.5 h time, assuming 0.6 s exposures with 5 dither points at each mapping point.

Table 1. Table of candidates.

RA	Dec	<i>J</i>	<i>H</i>	<i>K_s</i>
15 49 43.50	-36 06 53.4	17.013	14.904	14.980
15 49 50.89	-35 34 26.0	17.159	16.100	14.959
15 49 24.68	-35 35 12.5	16.413	15.472	14.952
15 49 29.17	-35 25 32.6	15.734	14.693	14.264
15 49 35.72	-35 34 14.5	15.201	14.163	13.812
15 48 45.36	-35 45 14.5	16.253	15.147	14.811
15 49 48.01	-35 36 57.3	15.950	14.862	14.629
15 51 44.17	-35 39 16.9	16.297	15.528	14.786
15 49 27.52	-35 39 15.2	16.912	15.903	14.918
15 50 10.36	-35 32 23.7	16.340	15.709	14.901
15 49 31.27	-35 29 24.0	16.160	15.111	14.510
15 49 32.24	-35 35 24.9	16.586	15.452	14.844
15 49 40.21	-35 27 27.5	15.657	14.733	14.340
15 51 43.21	-35 46 41.1	16.718	15.758	14.698
15 49 30.02	-35 36 52.5	16.245	15.230	14.933
15 49 18.83	-35 37 20.9	16.183	15.203	14.819
15 49 49.13	-35 33 48.5	16.460	15.662	14.817
15 49 30.48	-35 37 10.5	15.883	14.938	14.521
15 50 02.21	-35 31 57.2	16.063	15.199	14.495
15 49 54.42	-35 37 00.4	16.295	15.362	14.992
15 49 17.13	-35 39 34.3	16.283	15.434	14.704
15 50 57.33	-35 29 53.1	16.390	15.624	14.954
15 49 42.41	-35 36 48.9	15.734	14.566	14.230
15 51 38.26	-35 46 31.5	16.627	15.807	14.984
15 49 33.06	-35 28 56.8	16.554	15.478	14.968
15 51 27.21	-35 31 49.5	16.797	15.803	14.955
15 51 42.11	-35 34 20.4	16.254	15.558	14.934
15 49 39.25	-35 26 32.9	15.875	14.912	14.465
15 49 52.62	-35 35 26.5	16.014	14.792	14.600
15 49 52.19	-35 38 57.3	16.682	15.457	14.926
15 49 31.87	-35 25 23.8	14.830	13.716	13.360
15 49 51.73	-35 38 20.9	16.326	15.285	14.673
15 50 04.74	-35 23 35.9	16.347	15.511	14.949
15 49 31.35	-35 27 55.2	16.266	15.151	14.849
15 49 11.25	-35 52 23.6	16.109	14.361	14.699
15 47 27.81	-35 51 45.1	16.093	15.018	13.762
15 47 16.69	-35 29 03.0	16.089	14.995	14.630
15 48 35.23	-35 27 33.4	15.184	14.228	13.843
15 47 53.12	-35 42 51.1	16.249	15.323	14.869
15 49 29.10	-35 12 01.6	15.888	14.963	14.532
15 48 36.80	-35 29 31.7	15.961	15.242	14.619
15 48 43.38	-35 41 32.5	15.978	14.937	14.646
15 47 44.27	-35 23 29.7	15.703	14.881	14.332
15 47 26.17	-35 28 27.3	16.988	15.793	14.665
15 47 45.02	-35 26 59.3	15.639	14.720	14.267
15 48 59.86	-35 25 41.2	15.808	14.732	14.407
15 48 12.92	-35 16 07.9	15.864	14.789	14.412
15 47 16.35	-35 28 50.1	15.893	14.852	14.590
15 48 40.06	-35 39 24.3	15.749	14.878	14.445
15 47 55.09	-35 23 38.3	15.766	14.961	14.434
15 47 58.83	-35 26 07.7	16.621	15.703	14.965
15 48 22.95	-35 38 46.8	16.124	15.100	14.782
15 48 38.02	-35 34 55.7	16.254	15.422	14.914
15 49 15.28	-35 25 07.4	16.089	15.067	14.734
15 47 55.64	-35 21 24.2	16.463	15.359	14.997
15 47 37.47	-35 32 41.6	16.261	15.233	14.907

At a $S/N \sim 5$ sensitivity of 0.4 mJy, objects roughly ten times fainter than GQ Lup B could be detected.

We also looked at all 2MASS sources within 0.5 degree of GQ Lup to determine any brown dwarf candidates, using the criterion of the 2MASS brown dwarf searches, namely all objects with $K_s \leq 15.0$, $J - K_s \geq 1.3$ and no POSS counterparts, or $R - K_s \geq 5.5$ (Kirkpatrick et al. 1999, 2000). Additionally we require that a candidate have $K_s > 13.1$, the observed K_s of GQ Lup B, thus ensuring that the candidate is of a lower mass if at the same distance and age as GQ Lup. We find 56 candidates that would require further spectroscopic, Mid-IR, and proper motion follow-up that fit the near-IR photometry criteria and lack optical counterparts within $5''$. Their positions and 2MASS magnitudes are listed.

5. Conclusions

We have shown that the most probable scenarios for the formation of GQ Lup B. If it is a planet, it was most likely formed in the inner system and ejected outwards. Such a scenario will require the presence of a second planet in an orbit that will be between 2.5 AU and 10 AU, with significant eccentricity and an observational signature that may be detectable in the near future through radial velocity measurements or astrometry. If GQ Lup B is a very massive planet or brown dwarf, it is less clear how it formed. If it formed through an interaction between a brown dwarf binary and GQ Lup, then a nearby brown dwarf should have proper motion consistent with an ejection event.

Finally, it is interesting to speculate on the implications the confirmation of GQ Lup B's planetary status has for the frequency of planets in wide orbits. If GQ Lup B is a common occurrence, we would expect many other discoveries to have already been made. However, we can get an idea of the upper limit of this frequency by looking at a recent survey for substellar objects in wide orbits (McCarthy & Zuckerman 2004). For objects with masses $\sim 5 M_{\text{Jup}}$, this survey has found 0/42 stars with planets at separations >75 AU or an 80% probability that less than 4% of stars had planets at those separations. Assuming that GQ Lup B is $2 M_{\text{Jup}}$, the upper limit to the occurrence of such objects >75 AU would then be 2.5 times greater assuming the M^{-1} probability distribution of radial velocity surveys holds for this population of planets. However, more detailed observational work would need to be done to better constrain this frequency.

Since the uncertainty in GQ Lup B's mass is large and the upper limit for the mass is not planetary, the possibility remains that the object is a brown dwarf. Our results hold for any widely separated planet discovered. For example, the planets that are postulated to be present around Formalhaut and HR 4796A would imply the presence of another planet that is most likely more massive (Kalas et al. 2005; Wyatt et al. 1999).

This second planet should be in a closer orbit that is eccentric as well. Another example could be ϵ Eridani, with a confirmed planet at a semi-major axis of ~ 3.4 AU and an $0.1 M_{\text{Jup}}$ companion postulated at a semi-major axis of 40 AU based on the sculpting of ϵ Eridani's dust disk (Quillen & Thorndike 2002).

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