REPORT

EXOPLANETS

A giant exoplanet orbiting a very-low-mass star challenges planet formation models

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Surveys have shown that super-Earth and Neptune-mass exoplanets are more frequent than gas giants around low-mass stars, as predicted by the core accretion theory of planet formation. We report the discovery of a giant planet around the very-low-mass star GJ 3512, as determined by optical and near-infrared radial-velocity observations. The planet has a minimum mass of 0.46 Jupiter masses, very high for such a small host star, and an eccentric 204-day orbit. Dynamical models show that the high eccentricity is most likely due to planet-planet interactions. We use simulations to demonstrate that the GJ 3512 planetary system challenges generally accepted formation theories, and that it puts constraints on the planet accretion and migration rates. Disk instabilities may be more efficient in forming planets than previously thought.

About 4000 planets orbiting stars other than the Sun (exoplanets) have been discovered, but only about 10% are orbiting M-type dwarf stars (*1*), whose masses are typically below 0.6 solar masses ($M_\odot$), despite this being the most numerous stellar type in the Galaxy. This is largely an observational bias due to the intrinsic faintness of M dwarfs at visual wavelengths, where most exoplanet searches have been conducted. Statistical studies, based on radial-velocity and transit surveys (*2*, *3*), yield estimates of between 1 and 2.5 planets per M dwarf, most of them in the Earth- and Neptune-mass regime (*4*). Only a few Jupiter-mass planets have been found to orbit M dwarfs (*5*, *6*). This is consistent with predictions made using the core accretion theory of planet formation (*7*, *8*), which produce a low abundance of gas giants orbiting low-mass stars. Alternative planet formation theories, such as those involving disk instability, may explain the formation of gas giant planets in high-mass protoplanetary disks (*9*, *10*). Surveys using the microlensing technique indicate that gas giant planets may be more abundant at larger distances from their host stars (*11*, *12*), where transit and radial-velocity surveys are less sensitive. Some exoplanet formation scenarios suggest that the occurrence of gas giant planets should increase beyond the snow line (the distance from the star beyond which volatile compounds condense into the solid phase) in protoplanetary disks, but it remains unclear whether disks around M dwarf stars have sufficient mass and survive long enough to form gas giant planets (*7*, *13*). The CARMENES (Calar Alto High-Resolution Search for M Dwarfs with Exoearths with Near-Infrared and Optical Échelle Spectrographs) exoplanet survey (*14*) aims to address this issue by using a dual-channel (visible and near-infrared) high-resolution spectrograph to search for exoplanets around M-dwarf stars. Entering its fourth year, the CARMENES survey has now been observing for long enough to be sensitive to planets that orbit beyond the snow line of their parent protoplanetary disks. Relative to solar-type stars, the snow lines around M dwarfs lie closer to the star, with corresponding orbital periods above a few hundred days. Because the host star itself has a low mass, the radial-velocity signals induced by planetary companions are large enough to be detectable.

The M dwarf star GJ 3512 (also known as LP 90-18) is included in the CARMENES survey; its basic properties are summarized in Table 1. It is classified as an M5.5 main-sequence star, with a mass of about 0.12 $M_\odot$ and a distance from trigonometric parallax of 9.489 parsecs (*15*). We used procedures developed for other CARMENES survey stars (*16*) to compute the mass, radius, effective temperature, luminosity, and metallicity (the abundance of elements heavier than helium) from our spectroscopic observations. Initial observations of this target showed a clear trend in its radial velocity, which prompted an increase in the observational cadence from weekly to almost daily. We observed this target for more than 2 years, covering approximately four cycles of a large-amplitude periodic modulation in the radial velocity (Fig. 1A). Fitting a Keplerian orbit model to the data (*17*) gave consistent results for both wavelength channels, so we interpreted the signal as a planet. Simultaneous fitting of both channels yielded a planet minimum mass of $0.463^{+0.022}_{-0.023}$ Jupiter masses (M_J), on an eccentric orbit (eccentricity $e = 0.4356 \pm 0.0042$) with a period of 203.59 ± 0.14 days. The residuals of the best-fitting model were inspected for additional variability, showing a long-term trend in the data, again visible in both wavelength channels (Fig. 1B). Adding a second-order polynomial to the Keplerian motion improved the fit significantly relative to a linear

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model (*17*). This indicated that the residual radial velocities could be due to a second orbiting object with a period longer than ~1400 days. Therefore, we adopted a two-planet Keplerian model, but the long-period signal was poorly constrained, so we assumed a circular orbit for this object (Fig. 1) (*17*). No further statistically significant signals were identified in the dataset. Table 1 lists the parameters of our model, including the orbital and planetary properties derived for the detected planet GJ 3512 b and constraints for the candidate GJ 3512 c. The uncertainties were computed using standard Markov chain Monte Carlo (MCMC) procedures (*18*); we quote 68% credibility intervals.

The host star GJ 3512 is moderately magnetically active, as indicated by emission in the hydrogen Balmer Hα line (*19*). We performed photometric monitoring of the target at the Sierra Nevada, Montsec, and Las Cumbres observatories (*17*). The resulting light curves (fig. S3) show stellar variability with a period of around 87 days and peak-to-peak modulation of about 3%. Activity indices including the differential line width computed from the spectra (*20*) also show signals around the same period, with false-alarm probability below 0.1%. We attribute this variability to modulation caused by the rotation of the star, with a period that we estimate to be 87 ± 5 days (*17*). This value agrees with a previous report of an ~87-day rotation period for this star (*21*). The long rotation period and the kinematic properties indicate that the most likely age of GJ 3512 is within the interval 3 to 8 billion years (*17*). This is also consistent with its approximately solar metallicity. We rule out the possibility of the 204-day radial velocity variability arising from magnetic activity, because (i) this period is not present in the activity indicators, (ii) the radial-velocity amplitude is larger than expected for a moderately active slow-rotating star such as GJ 3512, and (iii) the radial-velocity amplitude does not vary with wavelength from the visible to the near-infrared. GJ 3512 has stellar parameters similar to those of the nearby planet-hosting star Proxima Centauri (*22*), but the planetary system is very different.

The detected planet's orbital inclination (i) is unknown, but values below 2° (i.e., nearly face-on) would be required for GJ 3512 b to have an absolute mass above the brown dwarf limit (~13 M_J). The probability of this object having a mass consistent with a planet is >99.9%, computed as the fraction of planetary orbits with inclinations greater than 2° assuming isotropic

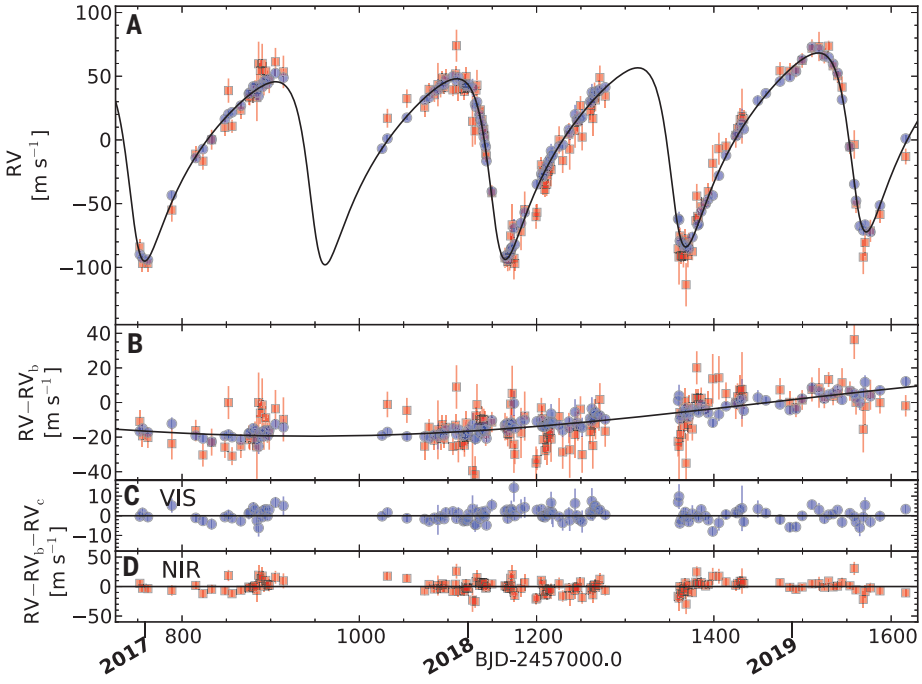


Fig. 1. Time series of radial-velocity data, orbital model, and residuals. (**A**) The radial-velocity time series obtained with the CARMENES visible (VIS; blue circles) and near-infrared (NIR; red squares) channels, and the best-fitting Keplerian orbital model (black solid line). (**B**) The same data and fits after removing the signal of the inner planet GJ 3512 b (RV$_b$), showing the radial velocity of the long-period candidate GJ 3512 c (RV$_c$). (**C** and **D**) The residuals between the best-fitting two-planet model and data for the two CARMENES channels. This model includes two Keplerian orbits, with the longer-period orbit assumed to be circular with P = 2100 days, which yields the best likelihood value. Black horizontal lines are guidelines, not fits to the data. Each panel has a different vertical scale; the horizontal axis is the time of the observations (BJD, barycentric Julian day). Calendar years are indicated for reference. Error bars denote the uncertainty of the radial velocity measurements.

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spatial orientations (*23*). Figure 2 shows the minimum mass of GJ 3512 b compared to known planetary systems as a function of their host star masses. GJ 3512 b lies in a region of the parameter space corresponding to low-mass stars with massive planetary companions, which are difficult to observe because of the faintness of the targets and the very low transit probability in wide orbits (<0.5% for GJ 3512 b, corresponding to $i > 89.7°$). The minimum mass ratio $q \sim 0.0034$ is lower than previous radial-velocity detections (Fig. 2). This system lies in a region of parameter space where only the microlensing technique has reported planet discoveries (*11*, *24*). However, the transient nature of microlensing detections and the large uncertainties of the host star masses limit analysis of those objects. The orbital and physical properties of GJ 3512 b and its host star are determined with better precision (Table 1). The occurrence rate of giant planets in orbits up to a few astronomical units around stars with masses below $0.3\,M_*$ is about 3%, estimated from microlensing surveys (*25*).

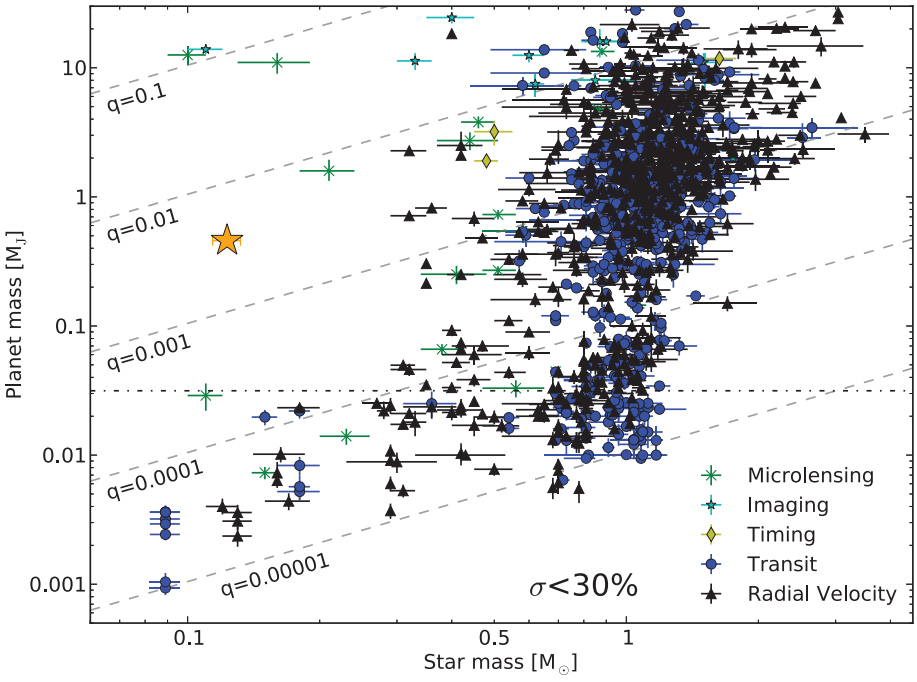


Fig. 2. GJ 3512 b's minimum planet mass compared to known planetary systems as a function of host star mass. Data for known planetary systems were taken from the NASA exoplanet archive (*1*). Only systems with uncertainties of <30% on both the star mass and planet mass are displayed (fig. S4 shows the same comparison without this constraint). Different exoplanet detection techniques are indicated with different symbols; GJ 3512 b is shown with an orange star. For the radial velocity and transit timing techniques, the planet minimum mass is plotted. Dashed lines indicate host star-to-planet mass ratios (q) as labeled, and the horizontal dot-dashed line corresponds to 10 Earth masses.

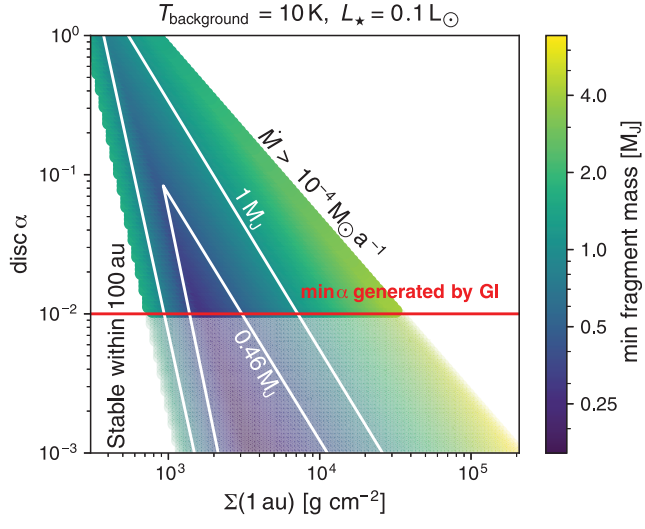


Fig. 3. Planet formation around GJ 3512 through gravitational instability. Gas giant planets can form through direct gravitational collapse of the gas disk if the disk is sufficiently dense. Formation prospects are shown as a function of the disk's surface density at 1 au (Σ) and its viscosity parameter α. In the white region at the left, the disk is gravitationally stable out to 100 au. The color scale and white contours show the minimum fragment mass, in Jupiter masses (*33*), that would form at the inner edge of the unstable region. In the white region at the right, accretion rates are unphysically high (*36*). The red line marks the lower limit on α that gravitational instability itself would generate through turbulence. Nearly all gravitationally unstable disks with realistic surface densities and accretion rates generate fragments in the mass range of the GJ 3512 planets. For reference, the minimum-mass solar nebula surface density value is around 1700 g cm^{-2} (*37*).

The high orbital eccentricity of GJ 3512 b is not expected for a system with only one planet, because interactions with the protoplanetary disk during orbital migration should lead to a circular or low-eccentricity orbit (*26*). However, planet-planet scattering can produce the often-large eccentricities of giant planets (*8*). Given the candidate second wide-orbit planet, inferred from the trend in the radial-velocity residuals after subtracting planet b, we suggest that a plausible route to the present orbital architecture is that the system formed initially with three planets, of which one (with a mass similar to or lower than that of planet b) was ejected, leaving GJ 3512 b on an eccentric orbit and a large gap between the two surviving planets (*17*).

GJ 3512 b has a very high mass for such a small host star, which, combined with the probably high planetary multiplicity at birth, poses a challenge for planet formation theories. We explored planet formation scenarios for the GJ 3512 system using pebble accretion models (*27*) without success (*17*). Formation of a gas giant in this way requires building up a large planetary core of at least 5 Earth masses. This is not possible around such a low-mass star, because the migration rate of planets is high. Therefore, planetary cores move rapidly to the inner edge of the disk. High disk masses are not favored by observations (*28*) but would not resolve the issue because they lead to both higher accretion and migration rates (*17*). The assumption of a longer disk lifetime of ~10 million years, as suggested from low-mass star observations (*29*), would still not explain gas giant formation in accretion models because the gas accretion time scales are too long for the small cores.

The total mass of the planets in the system ($\gtrsim 0.5\,M_J$ including at least GJ 3512 b and c, which is equivalent to ~0.4% of the host stellar mass) is large relative to the range of disk masses (~0.1 to 10 M_J) around low-mass pre–main-sequence M dwarfs (*30*), implying a very high planet formation efficiency. We therefore considered a competing model of planet formation by gravitational instability of the gas disk at very young ages, when the disk is still massive relative to the star (disk-to-stellar mass ratio $\gtrsim 0.1$) (*31*, *32*). For a range of disk viscosities α and surface densities Σ, the disk is gravitationally unstable at radii below 100 astronomical units (au) (Fig. 3) (*17*). The estimated masses of the fragments formed (*33*) are less than that of Jupiter, consistent with the mass of GJ 3512 b. Except for unrealistically low values of α, fragmentation of the disk occurs at radii of $\gtrsim$10 au,

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Table 1. Measured properties of GJ 3512 and its planet candidates. Stellar parameters of GJ 3512 were derived from the spectroscopy (*16*, *17*), mass and radius are given in solar units (M_* and R_*, respectively), and three-dimensional space velocities toward the Galactic Center (*U*), the galactic rotation direction (*V*), and the north galactic pole (*W*) are provided. Astrometric semi-amplitude and star-planet separation are given in milli–arc seconds (mas). Orbital and planetary parameters, and their uncertainties, were determined from the mean values and 68% credibility intervals of the distribution resulting from the MCMC analysis. Only lower limits were obtained for GJ 3512 c.

Stellar parameters	Value	
Spectral type	M5.5 V	
Mass (M_*)	0.123 ± 0.009	
Radius (R_*)	0.139 ± 0.005	
Luminosity (L_*)	0.00157 ± 0.00002	
Effective temperature (K)	3081 ± 51	
Distance (parsecs)	9.489 ± 0.008	
Rotation period (days)	87 ± 5	
Space velocities (km s^{-1})	U = −28.80 ± 0.37, V = −51.55 ± 0.17, W = 1.51 ± 0.30	
Metallicity (dex)	−0.07 ± 0.16	
Planet parameters	**Value**	
	GJ 3512 b	**GJ 3512 c**
Orbital period (days)	$203.59^{+0.14}_{-0.14}$	>1390
Radial velocity semi-amplitude (m s^{-1})	$71.84^{+0.34}_{-0.36}$	>12
Eccentricity	$0.4356^{+0.0042}_{-0.0042}$	—
Argument of periastron (°)	$125.49^{+0.71}_{-0.73}$	—
Time of periastron (barycentric Julian date, BJD)	$2457745.65^{+0.5}_{-0.5}$	—
Minimum mass $M \sin i$ (M_J)	$0.463^{+0.022}_{-0.023}$	>0.17
Orbital semimajor axis (au)	$0.3380^{+0.0080}_{-0.0084}$	>1.2
Minimum astrometric semi-amplitude $\alpha \sin i$ (mas)	$0.12753^{+0.00062}_{-0.00065}$	>0.15
Maximum planet angular separation (mas), i = 90°	$42.2^{+1.0}_{-1.1}$	>120
i = 8°	$51.1^{+1.2}_{-1.3}$	>120

so the planets must have migrated a substantial distance from their formation locations to their present positions. This is possible given the large mass of the disk with respect to the planet, and is often seen in numerical simulations of disk fragmentation (*33*, *34*). For realistic viscosity $\alpha > 0.01$, disk fragmentation typically occurs at radii of a few tens of au, and the total disk mass within this radius is ~30 M_J. Disks cannot extend too far beyond this fragmentation radius, because the total disk mass would become extremely large (up to 1 $M_\odot$ within 100 au). Thus, the planetary system around GJ 3512 favors the gravitational instability scenario as the formation channel for giant planets around very-low-mass stars.

For the orbital properties reported in Table 1, the reflex motion of the host star is predicted to be around 120 μas, about twice the expected accuracy of the Gaia astrometry mission (*35*) for a star of this brightness. The Gaia second data release (*15*) reports an excess noise for this source of 632 μas, which is statistically significant and could be partially attributed to the inner planetary companion. If all of the astrometric excess noise is due to the inner planet, this provides a lower limit for the inclination of about 8° and an upper limit for the planet mass of ~3.5 M_J. This excludes the face-on configurations discussed above. We estimate the star-planet contrast ratio in reflected light to be ~10^{-7} (depending on the albedo, inclination, and planet size), making it potentially detectable through direct imaging.

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the preparation of the manuscript. A.Re. co-led the CARMENES contribution and discussed the characterization of the system. F.F.B. and D.K. analyzed the CARMENES near-infrared spectra. E.H. obtained, reduced, and analyzed the TJO photometry. E.R., M.J.L.-G., and C.R.-L. coordinated the photometric follow-up of the targets at SNO observatory and analyzed the SNO photometry. F.J.Ac., V.C., and A.So. collected the SNO photometry. V.J.S.B., L.G.-C., R.Lu., and E.P. coordinated the photometric follow-up of the targets and obtained and reduced data from Las Cumbres Observatory. M.P., G.A.-E., T.T., and A.Ro. contributed to the analysis of the radial velocities. D.Baro. and M. Laf. analyzed the CARMENES spectra. J.A.C., M.C.-C., V.M.P., and A.Sc. derived the basic stellar parameters. L.T.-O. corrected and calibrated the CARMENES data. M.Z. reduced the CARMENES data. A.Q. and P.J. A. are the principal investigators of the CARMENES project. A.E., M.S., and R.M. contributed to the discussion and simulation of the formation scenarios. E.S. and M.L.F. are responsible for the CARMENES GTO archive. All authors except A.J.M., M.B.D., A.J., C.M., F.J.Ac., V.C., R.B., A.E., R.B., and A.So. contributed to the construction and operation of the CARMENES instrument.
Competing interests: The authors have no competing interests to declare. **Data and materials availability:** The CARMENES data are available at the Centro de Astrobiologia CARMENES archive, http://carmenes.cab.inta-csic.es/. All radial velocities, stellar activity indices, and photometric time series used in the paper are provided as machine-readable tables in data S1. Software scripts for our planet formation and evolution models are provided in data S2.

SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S8
Tables S1 to S6
References (*38*–*74*)
Data S1 and S2

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A giant exoplanet orbiting a very-low-mass star challenges planet formation models

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A small star hosts a big planet

M dwarfs, the most common type of star, are low-mass objects that emit most of their faint light in the near-infrared, making it difficult to detect any orbiting exoplanets. Morales *et al.* have observed the nearby M dwarf GJ 3512 in the optical and near-infrared (see the Perspective by Laughlin). Periodic variations in the star's radial velocity show that it hosts a gas giant exoplanet on an eccentric orbit. The authors use simulations to show that such a large exoplanet around such a small star has implications for models of planet formation.

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