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LETTERS

WASP-12b as a prolate, inflated and disrupting planet from tidal dissipation

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The class of exotic Jupiter-mass planets that orbit very close to their parent stars were not explicitly expected before their discovery[1]. The recently discovered[2] transiting planet WASP-12b has a mass $M = 1.4 \pm 0.1$ Jupiter masses (M_J), a mean orbital distance of only 3.1 stellar radii (meaning it is subject to intense tidal forces), and a period of 1.1 days. Its radius $1.79 \pm 0.09 R_J$ is unexpectedly large and its orbital eccentricity 0.049 ± 0.015 is even more surprising because such close orbits are usually quickly circularized. Here we report an analysis of its properties, which reveals that the planet is losing mass to its host star at a rate of about $10^{-7} M_J$ per year. The planet's surface is distorted by the star's gravity and the light curve produced by its prolate shape will differ by about ten per cent from that of a spherical planet. We conclude that dissipation of the star's tidal perturbation in the planet's convective envelope provides the energy source for its large volume. We predict up to 10 mJy CO band-head (2.292 μm) emission from a tenuous disk around the host star, made up of tidally stripped planetary gas. It may also contain a detectable resonant super-Earth, as a hypothetical perturber that continually stirs up WASP-12b's eccentricity.

Gas giant planets contract as they age and cool. Theoretical models[3,4] predict an upper radius limit of around $1.2R_J$ for mature Jupiter-like gas giants. The radii (R_p) of $\sim$60 short-period (mostly $P < 5$ days) gas giants have been measured from transit light curves. In the mass range $M_p \approx (1 \pm 0.5)M_J$, most planets have $R_p \approx (1.2 \pm 0.2)R_J$. However, several planets have observed R_p of about 1.5–$1.8R_J$. The rate of heat loss from these planets increases with their radius. The over-sized WASP-12b has an intrinsic radiative luminosity of $L_p \approx (1\text{–}2) \times 10^{28}$ erg s^{-1}. If gravity provides the only source with which to replenish this heat loss, WASP-12b would contract[3,5] significantly over 100 million years. The small orbital separation from its host star means that WASP-12b is one of the most intensely heated planets known. Stellar photons deposit energy onto a planet's day side, and reduce the internal heat loss[6], but the absorbed stellar irradiation is efficiently re-radiated along with the heat flux from a planet's interior on its night side[7]. Although surface evaporation enlarges a planet's tenuous atmosphere[8], it cannot alone significantly modify its internal structure and evolution[9].

To account for the inflated sizes of gas giants that are gigayears old, we consider additional heating mechanisms. Given its measured eccentricity $e_p \approx 0.05$ and its proximity to its host star, one potential suitable energy source for WASP-12b (and other close-in planets) is the dissipation of the stellar tidal disturbance[10] well below its photosphere. A planet's tidal heating rate $\dot{E}_{\rm tidal} \approx e^2 G M_p M_* / a\tau_e$ (where G is the gravitational constant and a is the semi-major axis) is determined by its circularization timescale τ_e (where subscript e indicates eccentricity damping), which is proportional to its tidal quality factor[11], Q'_p. (Here M_* is the stellar mass.) We note that many long-period planets have elongated orbits ($0 < e_p < 1$), whereas those of short-period gas giants are mostly circular (within the detection limit, $e_p < 0.02$). If this transition is due to their own lifelong tidal dissipation, their inferred $Q'_p \approx 10^6$ to 10^7.

For its orbit, WASP-12b's $\tau_e \approx 0.033 Q'_p (X_R/R_p)^5$ years, where $X_R \equiv (M_p/3M_*)^{1/3} a$ is the distance from the planet's core to its inner Lagrangian (L_1) point (that is, the Roche radius). If WASP-12b's $Q'_p \approx 10^7$, then its eccentricity would be damped within ten million years and the associated tidal heating rate would balance its current intrinsic radiative luminosity (that is, $\dot{E}_{\rm tidal} \approx L_p$). Depending on their internal structure and orbital periods, the magnitudes of Q'_p for gas giants and their host stars are thought to vary over a large magnitude range[12,13] (see below). If WASP-12b's Q'_p is comparable to that inferred for Jupiter[14] ($\sim 10^6$), its tidal heating would over-compensate beyond its intrinsic luminosity and would drive ongoing envelope expansion. Once the planet's atmosphere filled its Roche lobe, mass would be lost at a rate of $\dot{M}_p \approx \dot{E}_{\rm tidal} R_p / 2GM_p$.

To show that WASP-12b is currently losing mass, we analyse the amount of stellar light blocked during its primary transit by its cross-section in the (Y–Z) direction normal to the line (X) joining it and its host star (see Fig. 1). At the planet's occultation radius R_p and maximum Y distance ($Y_R = 2X_R/3$) on the planet's Roche lobe, we estimate the atmosphere density to be $\rho(R_p) \approx 5 \times 10^{-8}$ g cm^{-3} and $\rho(Y_R) \approx 3 \times 10^{-12}$ g cm^{-3} respectively (see Supplementary Information). An interesting consequence of the planet's prolate shape is that, as a function of orbital phase, it will scatter incident stellar flux, and emit its own thermal radiation, differently from how a spherical planet would. We estimate that this effect leads to 10% more flux during first and third quarters. Optical and mid-infrared orbit-modulated flux has been detected from several planets[15] and WASP-12b is a promising candidate for detection as well.

Near L_1, gas falls towards the host star through a nozzle with a radius $\Delta Y \approx 0.22 X_R$ (see Supplementary Information). The resultant pressure gradient on the Roche lobe drives gas from other regions to flow towards L_1. This advection along equipotential surfaces offsets the hydrostatic equilibrium normal to these surfaces. Consequently, the planet's lower atmosphere expands (see Fig. 1) at the speed of sound in space ($c_{\rm sound}$) across the Roche lobe (which has a total surface area of $A_R \approx 4\pi X_R Y_R$) with a mass flux $\dot{M}_{\rm observed} = \rho(Y_R) c_{\rm sound} A_R \approx 10^{-7} M_J$ per year. If WASP-12b's $Q'_p \approx 10^6$, its $\dot{M}_p \approx \dot{M}_{\rm observed}$ and its atmosphere loss would be continually replenished by the tidal inflation of its envelope.

Gas slightly beyond the nozzle accelerates towards the star and attains a free-fall speed v_f and a local density $\rho(L_1) \approx \rho(Y_R)$ $(c_{\rm sound} A_R / v_f \pi \Delta Y^2) \approx \rho(Y_R)$. Because $\rho(L_1) \ll \rho(R_p)$, this stream remains optically thin. It does not directly strike WASP-12 but forms a disk that is tidally truncated[16] by WASP-12b at about $0.7a = 3R_\odot$, where $R_\odot$ is the radius of the Sun. Provided WASP-12's magnetic field has a subsolar strength, the disk extends to the stellar surface and

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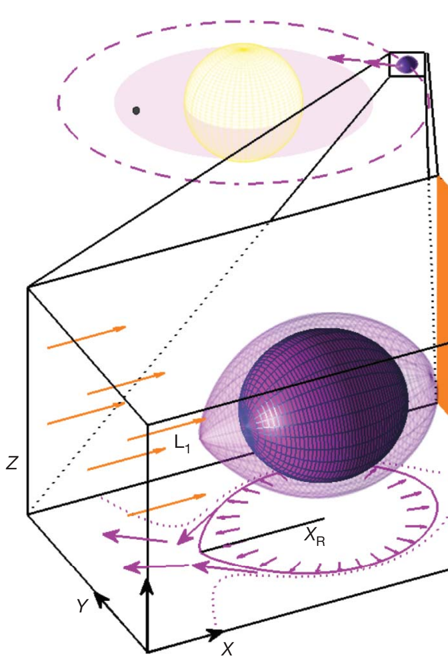

Figure 1 | WASP-12b's surfaces. The inner opaque purple surface (we note its prolate shape) contains the planet's envelope, which contributes to the eclipse of the stellar light, as inferred from transit observations. The stellar photons are represented by the orange arrows. The planet's outer transparent surface is the L_1 equipotential surface and its projection onto the orbital planet is shown as the solid purple line. The equipotential surfaces are computed assuming that the planet is a point mass on a nearly circular orbit. WASP-12b has a thin atmosphere that extends between these two surfaces; some of this atmosphere flows through the inner Lagrange point and eventually onto WASP-12. The purple dotted lines indicate the projection of the equipotential surface which channels the flow (purple arrows) from the planet's expanding envelope. The presence of a tenuous disk (light purple disk) with a hypothetical embedded planet (black dot) around WASP-12 (light yellow sphere) is illustrated at the top. The planet's orbit is traced by the purple dashed line. All variables are defined in the text.

intercepts a significant fraction ($\sim$0.1) of the stellar visual luminosity[17]. Viscous stress also generates heat at a rate of about $10^{-2}L_\odot$ while it transfers mass and angular momentum[18] (with an efficiency factor $\alpha \approx 10^{-2}$–10^{-3}) to produce a disk surface density $\Sigma \approx \alpha^{-1}\,{\rm g\,cm^{-2}}$.

The disk's warm ($\sim$3,000–4,000 K) midplane is sandwiched by heated surface layers that emit continuum and line radiation, respectively. At these temperatures, CO molecules are preserved and their 2-0 band-head emission at $\sim$2.292 μm (1–10 mJy at WASP-12's 267-kiloparsec distance from the Sun) is comparable to that of their continuum[19]. Although the expected flux is 1–2 orders of magnitude below that found around some known young stellar objects, this disk signature may be marginally observable with existing near-infrared spectrometers. Pollution of a few Earth masses of metals may also enhance the [Fe/H] of the star's low-mass $\left(<10^{-3}M_\odot\right)$ convection zone, depending on the efficiency of a double diffusive instability[20].

As its tidal debris flows through the disk onto the surface of its host star, WASP-12b gains orbital angular momentum. Its orbit also exchanges angular momentum with its host star at a rate that is regulated by the dissipative efficiency of its tidal perturbation within the stellar envelope[21,22]. WASP-12b would spiral towards its host star on a timescale of $\tau_{\rm a} \approx 10$ million years if the quality factor Q'_* of its slowly spinning host star is comparable to that ($\sim 10^6$) estimated from the circularization periods of binary stars in open clusters[23].

The low probability of catching a brief glimpse of WASP-12b's rapid orbital evolution and mass loss can be circumvented with variable Q'_* values[13]. We suggest that during WASP-12's main sequence evolution, its Q'_* may have been larger than 10^8, such that its planet's orbit did not evolve significantly. But, as it evolved onto its subgiant track, WASP-12's intrinsic oscillation frequencies would have been modified with the expansion of its radius, deepening of its convective zone, and slowdown of its spin. When these frequencies are tuned to match those of the planet's tidal perturbation, the star's dynamical response is greatly amplified. In these resonant episodes, Q'_* may have decreased[13] below $\sim 10^7$, leading to the present epoch of intense star–planet tidal interaction and dissipation.

Our result for the mass loss from WASP-12b is robust, whereas the tidal heating scenario depends on the assumed value of $Q'_{\rm p} < 10^7$ today. But the preservation of WASP-12b's finite eccentricity implies that its $Q'_p > 10^9$ for most of its lifetime. It is possible that during its recent accelerated orbital decay (owing to a decline in Q'_*), the evolving stellar perturbation frequency and strength may have intensified the planet's tidal response and dissipation over some ranges of its orbital period. The subsequent expansion of the heated envelope could have led to further changes in the planet's oscillation frequencies and enlarged the range of efficient tidal dissipation. We estimate an effective $Q'_{\rm p} \approx 10^6$ to 10^7 for the present-day WASP-12b, which is comparable to the value needed to maintain its inflated size.

It is also possible that WASP-12b's eccentricity is continually excited by one or more super-Earths with periods $P_2 < P$ and masses $M_2 < M_{\rm p}(P_2/P)^{13/3}$. Their convergent paths would lead to resonant capture[24] followed by lock-step orbital decay and e growth to an equilibrium[25]. Episodic declines of Q'_* and Q'_p (over a few million years) would excite WASP-12b's equilibrium eccentricity and inflate its radius to their observed values. Such a hypothetical planet would be embedded[16] in the circumstellar disk and the orbital migration induced by its tidal interaction with the disk[26] (on timescales $>10^8$ years) would not affect its resonant interaction with WASP-12b. The sensitivity of its radial velocity detection would need to be $<1\,{\rm m\,s^{-1}}$ and its transit observation would need to be 10^{-4} magnitude.

Our analysis can be used to constrain the efficiency of tidal dissipation of other close-in planets, such as the recently discovered[22] massive ($10M_{\rm J}$), short-period (0.94 days) planet WASP-18b. If it and its host star have similar Q' values of $\sim 10^6$, WASP-18b's tidal dissipation (at a rate of about $10^{30}\,{\rm erg\,s^{-1}}$) would maintain the synchronization of its spin[10] and induce mass loss through Roche-lobe overflow during the decay of its orbit (induced by the star's tidal dissipation) on a timescale of about one million years. However, WASP-18b is observed to have a normal radius ($1.1R_{\rm J}$) for massive gas giants, which places an upper limit ($<10^{28}\,{\rm erg\,s^{-1}}$) on the planetary dissipation rate[5], which implies either $Q'_* > 10^7$ or $Q'_{\rm p} > 10^{10}$ (or both). This constraint includes the possibility that WASP-18b will be preserved (with $Q'_* > 10^9$) until the end of its host star's main-sequence evolution.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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