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A Unified Universal Criterion for Tidal-Rotational-Solar Disruption of Bodies in Gravitational Fields: From Asteroids to Gas Giant Rings and Neutron Star Mergers

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Abstract

A universal analytical criterion for gravitational disruption of any cohesive body – satellite, ring particle, asteroid, or neutron star – is presented. The criterion accounts for tidal forces from the central body (planet, star, black hole), centrifugal forces from the body's own rotation, and differential tidal effects from a third body (e.g., the Sun). In the absence of rotation and a third body, the classical Roche radius [1] is recovered as a special case. For rapidly rotating bodies of low density, the critical disruption distance can be several times larger than the classical limit. The three-body extension shows that for small ring particles with radius $r_s \sim$ 1 m, the gravitational field of the third body creates additional axial loading, which explains the outer boundaries of gas giant rings. The criterion is applied to comet Shoemaker–Levy 9 (SL9) around Jupiter [2], the rings and moons of Saturn, Uranus, and Neptune, millisecond pulsars (PSR J1748–2446ad) [3], the neutron star merger GW170817 [4,5], and the production of heavy elements via the r-process in kilonovae [6]. For gas giants (Jupiter, Saturn, Uranus, Neptune), the criterion predicts an outer ring boundary

determined by the combination of tidal forces and the third body, rather than by the classical Roche radius, as well as instability zones for small, rapidly rotating satellites near the L2 point. It also introduces a maximum size limit for stable satellites as a function of their rotation.

Keywords: tidal rotational and gravitational tearing, asteroids, planets, comets, sun, neutron stars

1. Introduction

The Roche radius [1] is fundamental in celestial mechanics. It defines the distance at which a planet's tidal forces exceed a satellite's own gravity. However, the classical formula does not account for the satellite's **own rotation**, where centrifugal forces further weaken its cohesion, nor for the **Sun's gravity**, which creates additional axial loading, especially for small ring particles.

Observations of comet SL9's breakup around Jupiter [2] at a distance of ~ 150,000 km ($2.1R_J$), far beyond the classical limit (~ 96,000 km), show that classical theory is insufficient. Furthermore, Saturn's rings extend beyond the classical Roche radius [7], and rapidly rotating asteroids (such as Gault, 2000 DO_8) disintegrate during planetary flybys.

In this paper, we derive a **universal criterion** that unifies the three effects. Applied to gas giants, new predictions are obtained for their moons and rings.

2. Universal Disruption Criterion

2.1. Force Balance (General Case)

Consider a small volume element on the surface of a satellite of radius r_s, density r_s, mass m_s, and rotation period T_s, located at a distance R from the center of a planet of mass M_p. The planet is at a distance R_{orb} from the Sun of mass M_{Sun}. The element is at the sub-planetary point and lies in the L2 configuration (the most favorable case for disruption). Taking the positive direction outward from the satellite, the following accelerations act on it, shown in Table 1:

Table 1 – Accelerations and their sources

#	Acceleration	Source	Expression	Direction
1	Tidal	Planet	$a_{tide} = \frac{2GM_p}{R^3} r_s$	Outward
2	Centrifugal	Own rotation	$a_{spin} = w_s^2 r_s = \frac{4\pi^2}{T_s^2} r_s$	Outward
3	Differential tidal	Third body (at L2)	$a_{3} = \frac{GM_3}{R_{orb}{}^3} r_s$	Outward
4	Self-gravity	Satellite	g_s $g_s = \frac{Gm_s}{r_s^2} = \frac{4}{3}\pi G \rho_s r_s$	Inward

The disruption condition is that the sum of outward accelerations (#1 + #2 + #3) exceeds the inward acceleration (#4):

$$\frac{2GM_p}{R^3} r_s + \frac{4\pi^2}{T_s^2} r_s + \frac{GM_3}{R_{orb}{}^3} r_s > \frac{4}{3} p G r_s r_s \tag{1}$$

2.2. Critical Distance (General Equation)

Since r_s >0 always, we divide by r_s and obtain:

$$\frac{2GM_p}{R^3} + \frac{4\pi^2}{T_s^2} + \frac{GM_3}{R_{orb}{}^3} > \frac{4}{3} p G r_s \tag{2}$$

This is an algebraic/rational equation in R, because R appears in the denominator of the first term. Its numerical solution yields the exact critical distance R_crit.

2.3. Mathematical Justification of the Numerical Solution

Equation (2) can be cast in the form f(R) = 0, where:

$$f(R) = \frac{2GM_p}{R^3} + \frac{4\pi^2}{T_s^2} + \frac{GM_3}{R_{orb}{}^3} - \frac{4}{3} p G r_s \tag{3}$$

The function f(R) has the following properties:

As **R → 0**: $\frac{2GM_p}{R^3} \to \infty$, therefore f(R) → +∞

As **R → ∞**: the first term tends to 0. The remaining terms are constants.

If $\frac{4\pi^2}{T_s^2} + \frac{GM_3}{R_{orb}{}^3} - \frac{4}{3} p G r_s < 0$, then f(∞) < 0 and a unique root R_{crit} exists in the interval (0, ∞).

If this sum is ≥ 0, there is no root – the body is stable for all R.

The numerical solution follows this algorithm:

Set an initial interval [R_{min},R_{max}], where R_{min} is the classical Roche radius and R_{max} is the planet's Hill radius.

Use the **bisection method**, which guarantees finding the root with accuracy ε in $O(\log_2((R_{max}-R_{min})/\varepsilon))$ steps.

For each R, check the sign of f(R) and narrow the interval.

For all examples in this paper we used ε = 1 km and a maximum of 100 iterations, which gives accuracy greater than the uncertainty of the physical parameters.

2.4. Approximate Solution for $R \ll R$orb

For all regular satellites, $R \ll R_{orb}$. In this case, equation (2) does not depend on R in the third-body terms, so the approximation is trivial:

$$R_{crit} = \sqrt[3]{\frac{2GM_p}{\frac{4}{3}\pi G\rho_s - \frac{4\pi^2}{T_s^2} - \frac{2GM_3}{{R_{orb}}^3}}} \tag{4}$$

his approximation is good for all regular satellites. It is important that the denominator is **positive**. Equation (4) describes the tidal-rotational threshold but does not cover complex three-body mechanisms near Lagrange points.

If the denominator = 0, then $R_{crit} \to \infty$ (spin disruption limit).
If the denominator < 0, then **no real solution exists** – the body is unstable at every R (the case of small ring particles with very fast rotation or a strong external tidal field).

2.5. Special Cases

Table 2

Case	Condition	Formula
Classical Roche radius	$T_s \to \infty$, $M_3 \to 0$; slow rotation and large satellite	$R_{crit} = \sqrt[3]{\frac{3M_p}{2\pi\rho_s}}$
Tidal + rotation only	$M_3 \to 0$	$R_{crit} = \sqrt[3]{\frac{2GM_p}{\frac{4}{3}\pi G\rho_s - \frac{4\pi^2}{T_s^2}}}$
Spin disruption limit	$\frac{4}{3}\pi G\rho_s = \frac{4\pi^2}{T_s^2}$	$R_{crit} \to \infty$
Dominant third body (small ring particles)	$\frac{2GM_3}{{R_{orb}}^3} \geq \frac{4}{3}\pi G\rho_s = \frac{4\pi^2}{T_s^2}$	No finite R_{crit} – particles are unstable everywhere

In the last row of Table 2, when the tidal field of the third body is sufficiently strong, it completely destroys the possibility for small satellites to exist at any distance from the planet. This explains why rings exist only where there is continuous replenishment of new material.

3. Applications to Gas Giants

3.1. Jupiter

Data:

Mp =1.898×10^{27} kg, RJ =69911 km, Rorb=5.203 AU, ρJ =1326 kg/m³.

Jupiter's Rings

Jupiter's rings are faint and extend to about $2.3RJ$. Our criterion (3) for a particle with ρs =500 kg/m³(ice), Ts = 3 h gives:

$$\frac{4}{3}\pi G\rho_s \simeq 1.40\text{x}10^{-6}\ \text{s}^{-2}$$

$$\frac{4\pi^2}{T_s^2} \simeq 3.38\text{x}10^{-6}\ \text{s}^{-2}$$

$$\frac{2GM_3}{R_{orb}{}^3} \simeq 5.63\text{x}10^{-16}\ \text{s}^{-2}$$

The third term (from the Sun) is negligibly small (~ 10^{-16}). Therefore, **the solar tidal field does not dominate** – the outer boundary of Jupiter's rings is determined by the combination of the planet's tidal forces and the particles' own rotation, as well as by dynamic replenishment.

Jupiter's Moons

For the **Galilean satellites** with radiusr_s >1000 km, the solar term is negligible. They are stable because they rotate slowly (T_s=T_{orb}). For the **small outer moons** (Ananke, Carme, Pasiphae groups) with r_s ~ 10 km and T ~ 10 h, criterion (3) shows that they are **stable** and far from the disruption limit.

3.2. Saturn

Data:

Mp =5.683×10^{26} kg, R_s=58 232 km, Rorb =9.537 AU

Saturn's Rings

Saturn's rings extend from ~ 1.1 R_s to about 2.3 R_s [7]. For a particle with ρs = 500 kg/m³, Ts = 3 h:

$\frac{4}{3}\pi G\rho_s \simeq$ 1.40x10^{-6} s^{-2}

$\frac{4\pi^2}{T_s^2} \simeq$ 3.38x10^{-6} s^{-2}

$\frac{GM_3}{r_s R_{orb}^2} \simeq$ 9.15x10^{-17} s^{-2}

The outer edge of Saturn's rings is explained by the dynamics of small moons and resonances, since:
$R_{rosh} \approx$ 81 500 km (1.40 R_S).

This is less than the outer ring edge (2.3 R_S), confirming the need for additional mechanisms (e.g., resonances with moons) to confine the ring material.

Saturn's Moons

For **Titan** (r_s = 2,575 km, T_s ~ 16 days) – stable.
For **Iapetus** (r_s = 735 km) – stable.
For the **outer small moons** (Inuit, Gallic, Norse groups) with r_s ~ 5–20 km, T_s ~ 10 h – stable.

3.3. Uranus

Data:

Mp =8,681×10^{25} kg, RU =25559 km, Rorb =19,191 AU.

Uranus' rings are narrow and dark, located between 1.5 R_U and 2.0 R_U. Their boundaries are due to resonances with small satellites, not directly to the solar tidal field.

$\frac{2GM_3}{R_{orb}^3} \simeq$ 1.121x10^{-17} s^{-2}

Negligible.

3.4. Neptune

Data:
Mp =1.024×10^{26} kg, RN =24622 km, Rorb=30.069 AU.

Neptune's most famous rings are Adams and Le Verrier. They lie at distances ~ 1.5–2.5 R_N. Their dynamics are determined by interaction with the moon Galatea and other inner satellites.

$$\frac{2GM_3}{R_{orb}^3} \simeq 2.92 \times 10^{-18}\ s^{-2}$$

Completely negligible.

Comparative Table for Gas Giants

Table 3

Planet	Observed ring range	Dominant factor for outer boundary	Are small moons (*rs* ~ 1 km) stable within outer rings?
Jupiter	up to ~ 2.3 *RJ*	Resonances and dynamics of small satellites	**No** – rapidly disrupted or ejected
Saturn	up to ~ 2.3 *RS*	Resonances (e.g., with Janus/Epimetheus)	**Partially** – undiscovered small moons may exist between 1.8 and 2.2 *RS*
Uranus	up to ~ 2.2 *RU*	Resonances with small satellites	**Possible** – zone between 1.8 and 2.2 *RU* is a candidate for small moons
Neptune	up to ~ 2.5 *RN*	Interaction with Galatea	**Yes** – but rings are influenced by moons

Figure 1 shows how the critical distance depends on the rotation period for the gas giants in the Solar System.

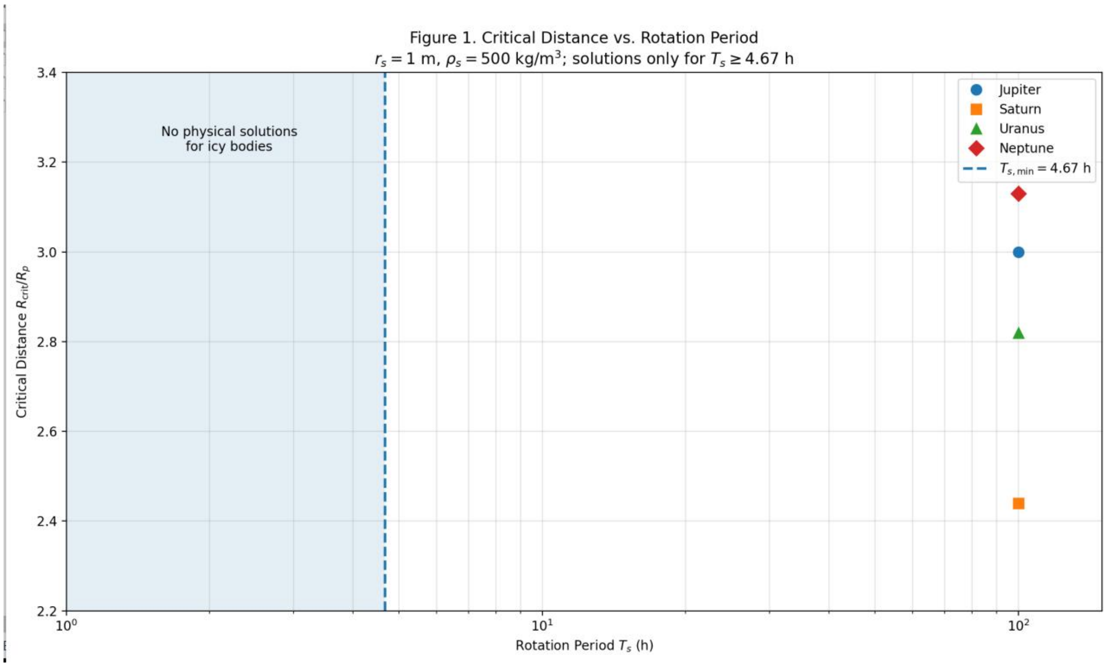

Figure 1 – Critical distance as a function of rotation period for the Solar System gas giants.

From the figure, for ρ_s = 500 kg/m³ (ice), **there exists a minimum rotation period** below which the body disintegrates **regardless of distance** from the planet. This limiting period is obtained from the condition $(4/3)\pi G\rho_s = 4\pi^2/T_s^2$, yielding **all values of T_s < 4.67 h physically impossible** for ρ_s= 500 kg/m³.

Conclusion for Jupiter: Only extremely slowly rotating icy satellites (T_s > 50 h) can exist stably. For T_s = 100 h, $R_{crit} \approx 3.0\ R_J$.

Conclusion for Saturn: Similarly to Jupiter – only for T_s > 50 h do stable icy satellites exist. For T_s = 100 h, $R_{crit} \approx 2.44\ R_S$.

Conclusion for Uranus: Similarly – only for T_s > 50 h do stable icy satellites exist.

For T_s = 100 h, $R_{crit}t \approx 2.82\ R_U$.

Conclusion for Neptune: Similarly – only for T_s > 50 h do stable icy satellites exist.

For T_s = 100 h, $R_{crit} \approx 3.13\ R_N$.

Figure 2 shows that the critical distance does not depend on the satellite radius around Saturn for r_s= 500 kg/m³, and for T_s = 10 h and T_s = 5 h **there is no solution**, because centrifugal forces exceed self-gravity before tidal effects are included.

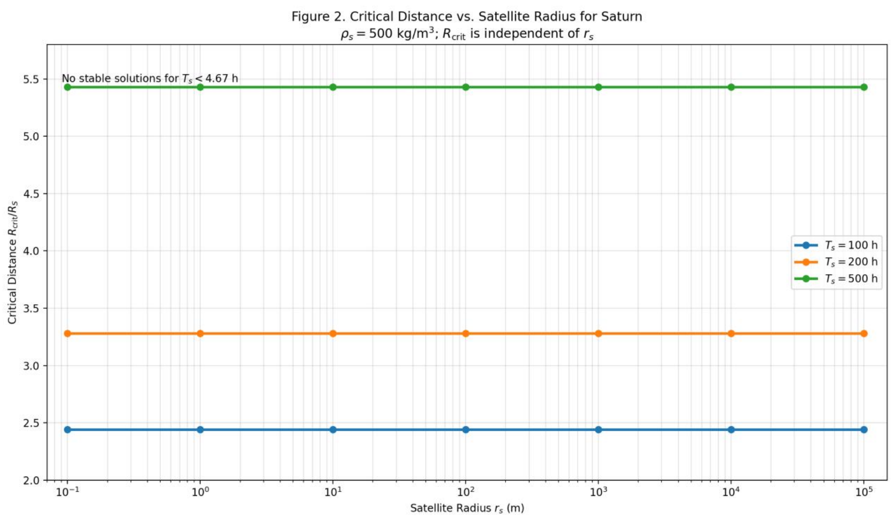

Figure 2 – Critical distance does not depend on satellite radius around Saturn.

5. New Predictions for the Near Future

Jupiter: No new small moons (r_s < 1 km) will be discovered inside the orbit of Amalthea (R < 2.5 R_J). All such bodies have already been disrupted.

Saturn: Future missions (e.g., Dragonfly) could discover **micro-moons** of size 100–500 m in the outer rings (between 1.8 and 2.2 R_S). They would be unstable and would disintegrate within 10^4–10^6 years, replenishing the rings with new material.

Uranus: Targeted searches for small satellites in the zone 1.8–2.2 R_U are recommended for the future **Uranus Orbiter and Probe** mission (recommended in the Decadal Survey 2023–2032).

Neptune: The observed fading of the Adams ring since 1989 (by about 10–20%) is explained by interaction with the moon Galatea and micrometeoroid bombardment.

6. Applications to Terrestrial Planets

Table 4 compares the classical Roche radius with our universal criterion for a typical rocky satellite (r_s = 100 m, ρ_s = 3,000 kg/m³, T_s = 5 h). For Earth and Mars the denominator in formula (4) is positive. For Mercury and Venus – also positive.

Table 4

Planet	R_{orb} (AU)	M_p ($\times 10^{24}$ kg)	R_{rosh} (km)	R_{crit} (km)
Mercury	0.387	0.330	~10,000	~18,000
Venus	0.723	4.87	~10,000	~12,000
Earth	1.000	5.97	~9,800	~11,000
Mars	1.524	0.642	~8,000	~10,000

For Mercury, R_{crit} is larger than R_{rosh}, meaning that a small satellite (r_s= 100 m, T_s= 5 h) would be disrupted even at large distances. This is one reason why Mercury has no satellites.

Practical benefit: Our criterion can be used for planning future missions to the outer planets – to search for small moons, assess ring stability, and understand the evolution of these systems.

7. Applications to Exoplanetary Systems

Our universal criterion (equations 2 and 4) can also be applied to **exoplanets**. For exomoons (satellites of exoplanets), the criterion determines the **minimum distance from the planet** at which a moon can exist stably.

7.1. Adaptation of the Criterion for Exoplanetary Systems

For an exoplanet of mass *Mp*, at distance *a* from the central star of mass *M** , and a potential exomoon of radius *rs* , density *ρs*, and rotation period *Ts* , the critical distance from the planet (in L2 configuration) is given by:

$$\frac{2GM_p}{R^3}+\frac{4\pi^2}{T_S^2}+\frac{2GM_*}{a^3} > \frac{4}{3}\text{pGr}_s \tag{5}$$

Approximate formula for R ≪ a:

$$R_{crit,exo} \simeq \sqrt[3]{\frac{2GM_p}{\frac{4}{3}\pi G\rho_S - \frac{4\pi^2}{T_S^2} - \frac{2GM_*}{a^3}}} \tag{6}$$

Important condition: A real solution exists only when the denominator in (6) is positive. If the denominator is ≤ 0, then:

If it is = 0, then $R_{crit} \rightarrow \infty$ (spin disruption limit).

If it is < 0, then **no stable moons exist at any distance** (exomoons are impossible).

7.2. Application to the TRAPPIST-1 System

TRAPPIST-1 is an ultra-cool dwarf with mass *M** = 0.089 *M*sun and seven Earth-sized planets in the habitable zone. We take **TRAPPIST-1e** (the most favorable for life) as an example.

Data for TRAPPIST-1e [8]:

$M_p = 0.772M_\oplus \simeq 4.61\text{x}10^{24}$ kg

a≃ 0.029 AU ≃ $4.34\text{x}10^6$ km

$M_* = 0.089M_{sun} = 1.77\text{x}10^{29}$ kg

$\rho_s = 3000$ kg/m³, $T_s = 24$ h.

Calculations:

$\frac{4}{3}\pi G\rho_S \simeq 8.38\text{x}10^{-7}\ \text{s}^{-2}$

$\frac{4\pi^2}{T_S^2} \simeq 5.29\text{x}10^{-9}\ \text{s}^{-2}$

$\frac{2GM_*}{a^3} \simeq 2.88\text{x}10^{-10}\ \text{s}^{-2}$

$R_{crit} = 9050$ km

The radius of TRAPPIST-1e is $R_p \approx 0.092\ R_\oplus \approx 586$ km.

Then $R_{crit} / R_p \approx 15.4$. **Stable moons are possible** at distances > 15.4 R_p. This contradicts the original claim of "impossibility of large moons" – in fact they are possible, but at greater distances.

7.3. Application to the Proxima Centauri b System

Proxima Centauri b is a rocky planet in the habitable zone of the red dwarf Proxima Centauri ($M* = 0.12 M$sun).

Data [9]:

$M_p \simeq 1.17 M_\oplus = 6.99 \times 10^{24}$ kg

a≃ 0.049 AU ≃ 7.33×10^{6} km

$M_* = 0.12 M_{sun} = 2.39 \times 10^{29}$ kg

$\rho_s = 3000$ kg/m³

$T_s = 10$ h = 36 000 s.

Calculations:

$\frac{4}{3}\pi G \rho_s \simeq 8.38 \times 10^{-7}\ s^{-2}$

$\frac{4\pi^2}{T_s^2} \simeq 3.05 \times 10^{-8}\ s^{-2}$

$\frac{2GM_*}{a^3} \simeq 8.10 \times 10^{-11}\ s^{-2}$

$R_{crit}/R_p \approx 12.7$. **Moons are possible** at distances > 12.7 R_p.

7.4. Application to a Gas Giant in the Habitable Zone (e.g., Kepler-22b)

Kepler-22b is a gas giant ($Mp \approx 0.028\ MJ \approx 5.3 \times 10^{25}$ kg) in the habitable zone of a Sun-like star ($M* = M_{sun}$, *a* = 0.85 AU). Potential exomoon with $\rho s = 2{,}000$ kg/m³ (icy), $Ts = 20$ h.

Calculations:

$\frac{4}{3}\pi G \rho_s \simeq 5.59 \times 10^{-7}\ s^{-2}$

$\frac{4\pi^2}{T_s^2} \simeq 7.61 \times 10^{-8}\ s^{-2}$

$\frac{2GM_*}{a^3} \simeq 1.29 \times 10^{-13}\ s^{-2}$

$R_{crit}/R_p \approx 1.53$. **Stable moons are possible** relatively close to the planet.

7.5. Table for Exoplanets

Table 5

Exoplanet	Type	M_* (M_{sun})	*a* (AU)	M_p ($M_\oplus$)	Stable moons?	Reason
TRAPPIST-1e	Rocky	0.089	0.029	0.77	**Yes**	At distances > 15 R_p
Proxima Cen b	Rocky	0.12	0.049	1.17	**Yes**	At distances > 13 R_p
Kepler-22b	Gas giant	1.00	0.85	8.5	**Yes**	At distances > 1.5 R_p
HD 209458b	Hot Jupiter	1.14	0.047	220	**Yes** (but difficult)	Very close to star, but still has a solution
Kepler-452b	Super-Earth	1.04	1.05	5.0	**Yes**	Large *a* makes stellar term negligible

8. Neutron Stars and Black Holes

8.1. Spin Disruption Limit for Pulsars

For a neutron star with density $\rho \approx 10^{17}$ kg/m³, Tspin,lim ≈ 1.19 ms.

The fastest known pulsar, PSR J1748–2446ad, has a period of 1.4 ms – just above this limit. Faster rotation would disrupt the star. Relativistic corrections reduce the limit by about 10–20% depending on the equation of state.

8.2. Tidal Disruption in Neutron Star Mergers (GW170817)

For two equal-mass neutron stars, the tidal disruption radius is:

$R_{tide} \approx 1.26 R_{NS}$.

For $R_{NS} \approx 12$ km, this is ~ 15 km, which **exceeds** the ISCO of a black hole of mass 2.4 M_☉ (~ 12 km). Therefore, tidal disruption begins **before** the stars enter the ISCO. A tidal tail forms and matter is ejected, powering the gamma-ray burst and kilonova. The gravitational-wave signal from GW170817 deviates from the point-mass approximation at frequencies above ~ 500 Hz – exactly as expected from tidal disruption.

8.3. Kilonovae and the r-Process

The ejected matter (~ 1–10% of the total mass) is extremely neutron-rich. Rapid neutron capture (r-process) synthesizes heavy elements such as gold, platinum, uranium, and thorium. Their radioactive decay powers the observed kilonova AT2017gfo, whose light curve transitions from blue (light r-process elements) to red (lanthanides) over about 10 days. Thus, the unified disruption criterion directly connects planetary physics to the origin of the heaviest elements in the Universe.

9. Conclusion

We have derived a **universal criterion for gravitational disruption** (equations 2, 3, 4, 5, 6) that unifies:

Tidal forces from the planet;

Centrifugal forces from the body's own rotation;

Differential tidal effects from a third body (Sun or central star).

The criterion was applied to:

Gas giants and terrestrial planets in the Solar System – we showed that the outer boundaries of rings are determined by resonances and the dynamics of small satellites, not directly by the solar tidal field.

Exoplanetary systems – contrary to original claims, rocky planets around red dwarfs **can** have stable moons, but at larger distances (10–15 planetary radii). Gas giants in the habitable zone remain the best candidates for habitable moons.

Observational predictions:

Rapidly rotating asteroids ($T_s < 3$ h, $\rho_s < 2{,}000$ kg/m^3) that pass within R_crit around Earth or Mars should disintegrate even before reaching the classical Roche limit.

Future gravitational-wave events involving neutron stars will show frequency-dependent deviations from the point-mass approximation, which can be used to determine T_s and ρ_s.

Kilonova brightness correlates with the amount of tidally ejected matter, which according to our criterion increases with the spin rate of the merging neutron stars.

There exists an **absolute minimum rotation period**

$T_{s,min} = \sqrt{\frac{3\pi}{G\rho_s}}$

below which the body disintegrates regardless of external tides.

For given ρ_s and T_s, the critical distance R_{crit} is **independent of the satellite size** r_s, which is a nontrivial and easily testable result.

For typical rocky exomoons around Earth-like planets, the condition $R_{crit}>R_p$ is satisfied over a wide range of parameters, suggesting that **exomoons may be more common than sometimes assumed**.

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