The Radio Sky

Lecture 9

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Retrieval: classify this burst

An unresolved radio burst

- Duration: a few milliseconds
- Nearly 100% circularly polarized
- Inferred brightness temperature far above 10^{12} K

Which class of emission mechanism is required? Which familiar mechanism is excluded, and why?

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Which class of emission mechanism is required? Which familiar mechanism is excluded, and why?

- Coherent emission: $T_{\rm b}$ exceeds the incoherent-synchrotron ceiling of $\sim 10^{11}$–10^{12} K (Lecture 8) by a wide margin.
- Incoherent synchrotron is excluded: it would have to be beamed by an implausible Doppler factor, and it gives little circular polarization.
- Candidates: a maser process in a magnetized plasma, or plasma emission. Today: how to tell, and what the frequency then measures.

Central question and the three regimes

Why do some magnetically active objects emit highly polarized, extremely bright, narrow-band radio bursts?

	Cyclotron	Gyrosynchrotron	Synchrotron
Lorentz factor	$\gamma - 1 \ll 1$	$\gamma \sim 1$–3	$\gamma \gg 1$
Electron energy	$\lesssim$ few keV	10 keV–few MeV	$\gg$ MeV
Harmonics emitted	$s = 1$–3	$s \sim 10$–100	$s \gg 100$: continuum
Spectrum	lines at $s\nu_{\mathrm{G}}$	broad, peaked	power law
Circular pol.	high	tens of %	small
Typical B	G–kG	10^2–10^3 G	μG–G

- ν_{G}: the electron gyrofrequency (defined next slide).
- All three are *incoherent* unless a population inversion amplifies the radiation: then electron-cyclotron maser (ECM) emission.
- Units: SI, with B in gauss as is conventional in stellar and planetary work ($1\,\mathrm{G} = 10^{-4}\,\mathrm{T}$).

Gyrofrequency and harmonics

Electron (charge $-e$, mass m_e) in a uniform field B (Lecture 4; a relativistic electron gyrates at ν_G/γ). The electron gyrofrequency is its rotation frequency:

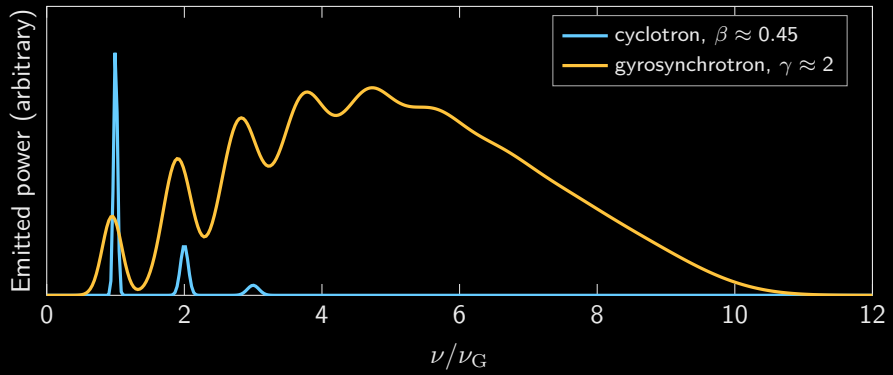
$$\nu_\mathrm{G} = \frac{eB}{2\pi m_\mathrm{e}} = 2.80\,\mathrm{MHz}\left(\frac{B}{\mathrm{G}}\right)$$

- Emission occurs at harmonics, Doppler shifted by motion along B:

$$\nu = \frac{s\,\nu_\mathrm{G}}{\gamma\,(1-\beta_\parallel\cos\theta)}, \qquad s = 1, 2, 3, \ldots$$

- θ: angle between B and the line of sight; $\beta_\parallel = v_\parallel/c$.
- Non-relativistic limit: power in harmonic s falls roughly as $\beta^{2(s-1)}$, so only the first few harmonics matter.
- As γ rises, harmonics multiply and broaden until they merge into the synchrotron continuum (Lecture 4).
- Notation: ν_G is also written ν_c or ν_B.

From harmonic lines to a continuum



Schematic of single-electron emission; amplitudes and widths illustrative only.

- Line broadening comes from the spread in γ and $\beta_{\parallel} \cos\theta$.
- Gyrosynchrotron emission from a distribution of electrons is smooth: its spectral shape constrains B and the electron energies.

Gyrosynchrotron emission from flares and active stars

- Power-law electrons (10 keV–MeV) in $B \sim 10^2$–10^3 G loops.
- Peak at tens of harmonics: several GHz in solar flares.
- Below the peak: self-absorbed. Above: optically thin, steeper than the synchrotron $-(p-1)/2$ for the same p.
- Circular polarization tens of per cent; sense can reverse across the peak.
- Active stars (RS CVn binaries, dMe flare stars): $T_\mathrm{b} \sim 10^8$–10^{10} K, broad-band, moderately polarized.

Incoherent ceiling

As for synchrotron (Lecture 8):

$$T_\mathrm{b} \lesssim T_\mathrm{eff} \sim E/k_\mathrm{B}$$

$E = 100$ keV: 1.2×10^9 K.
$E = 1$ MeV: 1.2×10^{10} K.

Reviews: Dulk 1985 (doi:10.1146/annurev.aa.23.090185.001125); Güdel 2002 (doi:10.1146/annurev.astro.40.060401.093806).

How coherent emission beats the ceiling

Radiative transfer with excitation temperature $T_{\rm ex}$ and optical depth τ_ν (Lecture 3):

$$I_\nu = I_\nu(0)\,\mathrm{e}^{-\tau_\nu} + B_\nu(T_{\rm ex})\,(1 - \mathrm{e}^{-\tau_\nu})$$

- Thermal or incoherent emitters: $\tau_\nu > 0$, so $T_{\rm b} \leq T_{\rm eff}$.
- Population inversion: stimulated emission exceeds absorption, the absorption coefficient is negative, $\tau_\nu < 0$.
- Radiation grows as $\mathrm{e}^{|\tau_\nu|}$: $T_{\rm b}$ is limited only by saturation, not by particle energies.

Plasma emission

At $\nu \approx \nu_{\rm p}$ or $2\nu_{\rm p}$, driven by electron beams. Frequency measures density. Solar Type III bursts (Lecture 13).

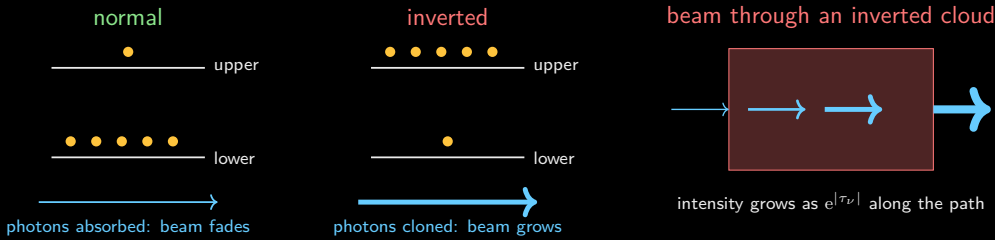
Electron-cyclotron maser

At $\nu \approx s\nu_{\rm G}$, $s = 1$ or 2. Frequency measures field strength. Needs $\nu_{\rm p} \ll \nu_{\rm G}$.

Plasma frequency: $\nu_{\rm p} \approx 8.98\,\mathrm{kHz}\,(n_{\rm e}/\mathrm{cm}^{-3})^{1/2}$.

What is a maser?

Microwave Amplification by Stimulated Emission of Radiation. A passing photon can make an excited atom emit a *clone* of itself: same frequency, direction and phase.



- Normally more atoms sit in the lower level, so absorption wins. A pump (collisions or radiation) can put more atoms in the upper level: then each photon triggers more emission than absorption.
- The result is an avalanche: a laser, but at radio wavelengths.

A laser versus filtered lamplight

Take two red (650 nm) sources of the *same power*, 1 mW, leaving the same 1 mm-diameter aperture: a laser pointer, and a hot filament lamp behind a 10 nm-wide red filter.

	Laser pointer	Filtered lamp
Power, aperture	1 mW, 1 mm	1 mW, 1 mm
Solid angle of the beam	8×10^{-7} sr (1 mrad)	$\sim \pi$ sr
Bandwidth	~ 1 GHz	~ 7000 GHz
Spectral radiance I_ν ($\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$)	~ 2	$\sim 6 \times 10^{-11}$
T_b (Planck inversion)	$\sim 2 \times 10^{10}$ K	$\sim 2 \times 10^{3}$ K

- The laser is $\sim 3 \times 10^{10}$ times brighter at its frequency: a factor $\sim 4 \times 10^{6}$ from squeezing the power into a narrow beam and $\sim 7 \times 10^{3}$ from squeezing it into a narrow band.
- Filtered thermal light can never exceed the lamp temperature. Only stimulated, coherent emission breaks that limit, in the laboratory as in the sky.

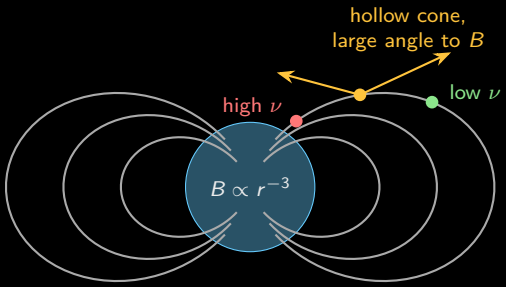
Illustrative round numbers; the filament is at ~ 2200 K.

Conditions for the electron-cyclotron maser

1. Low density, strong field: $\nu_{\rm p}/\nu_{\rm G} \ll 1$, so that the extraordinary (x) mode can be emitted at the fundamental and escape.
2. Inverted distribution: more electrons at higher perpendicular momentum, $\partial f/\partial p_\perp > 0$ in some region.
   - *Loss cone*: small-pitch-angle electrons precipitate into the atmosphere; the reflected population lacks them.
   - *Horseshoe/shell*: electrons accelerated along B into a converging field convert $p_\parallel$ to $p_\perp$.
3. Relativistic resonance: $\nu = s\nu_{\rm G}/\gamma + k_\parallel v_\parallel/2\pi$. Even for keV electrons ($\gamma - 1 \sim 10^{-2}$) the $1/\gamma$ term makes the resonance sample $\partial f/\partial p_\perp > 0$: net growth.

- Theory: Wu & Lee 1979 (doi:10.1086/157120); solar and stellar bursts: Melrose & Dulk 1982 (doi:10.1086/160219); review: Treumann 2006 (doi:10.1007/s00159-006-0001-y).
- Qualitative treatment only: the growth-rate calculation needs plasma kinetic theory (later course).

Observable consequences of ECM emission



Schematic dipole magnetosphere.

- Narrow band: each point emits near its local ν_{G}. A source moving along a field line drifts in frequency.
- Frequency maps altitude: ν_{max} comes from the strongest field, near the surface footpoint.
- $\sim$100% circular: a single (x) mode; sense set by the field direction in the source hemisphere.
- Beamed into a thin hollow cone at a large angle to B: rotation sweeps the cone past us, giving periodic pulses or arcs in the dynamic spectrum.

Concept test

Question

Assuming fundamental ECM emission, a burst at 280 MHz implies what local magnetic field, if $\nu_{\rm G} = 2.8\,{\rm MHz} \times (B/{\rm G})$?

Concept test

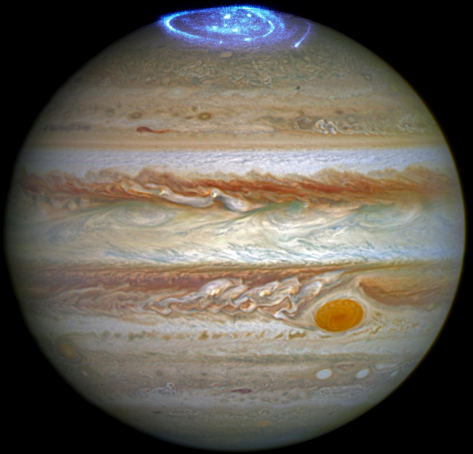
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Answer: $B = 100$ G

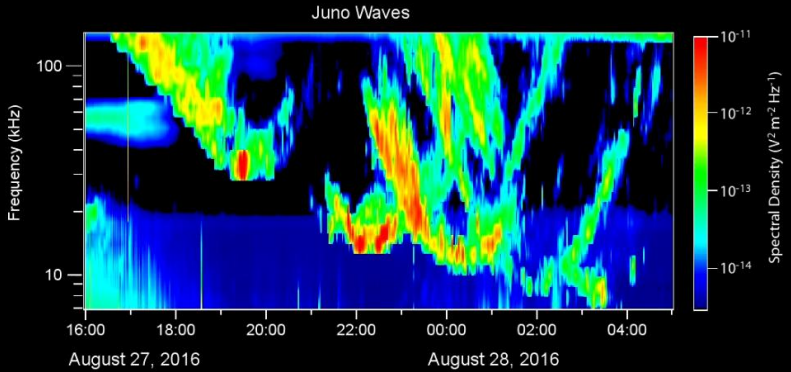
1. Rearrange: $B = \nu/(2.8\,\mathrm{MHz})$ in gauss.
2. $280/2.8 = 100$, so $B = 100$ G (50 G if second harmonic).

Jupiter: auroral footprints of the radio-emitting electrons



Credit: NASA, ESA, and J. Nichols (University of Leicester); images.nasa.gov. HST ultraviolet aurora over an optical image.

Jupiter's auroral radio emission in a dynamic spectrum



Credit: NASA/JPL-Caltech/SwRI/Univ. of Iowa (PIA21037), images.nasa.gov. Juno Waves, 7–140 kHz, 27–28 Aug 2016.

Reading the dynamic spectrum

- Axes: time (13 h) and frequency (kHz); colour is spectral density.
- Emission occupies narrow, drifting arcs rather than filling the band: the beaming geometry changes as Juno and the planet move.
- Wavelengths of $\sim$km: the kilometric component. Jupiter's decametric emission has an upper cutoff near 40 MHz: with fundamental ECM, $B = 40/2.8 \approx 14$ G in the polar source region.
- Juno crossed hectometric source regions and measured loss-cone electron distributions able to drive ECM (Louarn et al. 2017, doi:10.1002/2017GL072923). Review: Zarka 1998 (doi:10.1029/98JE01323).

Pitfall

A dynamic spectrum shows what is beamed *towards the observer*. Gaps can be geometry, not absence of emission.

Concept test

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The Juno spectrum covers 7–140 kHz. Which telescope recorded it, and could a ground-based telescope such as LOFAR or the GMRT observe the same waves?

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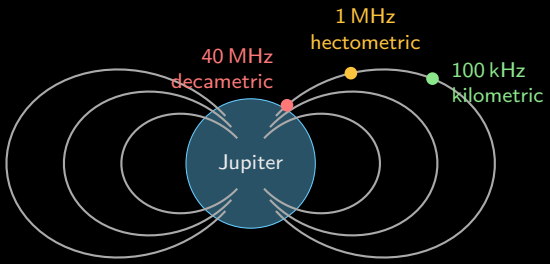
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The Juno spectrum covers 7–140 kHz. Which telescope recorded it, and could a ground-based telescope such as LOFAR or the GMRT observe the same waves?

Answer: a spacecraft was needed, but part of Jupiter's emission is observable from the ground

1. No telescope: the data come from the *Waves* antennas on the Juno spacecraft, in situ. Below the ionospheric plasma frequency $\nu_\mathrm{p} \approx 9\,\mathrm{kHz}\,(n_\mathrm{e}/\mathrm{cm}^{-3})^{1/2} \approx$ 5–10 MHz radio waves cannot reach the ground, so kHz emission is invisible from Earth.
2. Jupiter's decametric emission (up to ≈ 40 MHz) does pass through, and is observed from the ground at $\gtrsim 10$ MHz (LOFAR, NenuFAR, UTR-2). The GMRT (above 150 MHz) is too high in frequency.

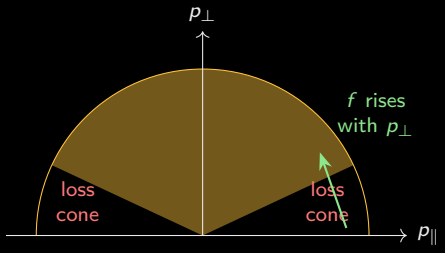
Jupiter and the ECM conditions: strong field, low density



Schematic, not to scale: $\nu \approx \nu_{\mathrm{G}} \propto r^{-3}$.

- Strong field: polar surface $B \approx 14\,\mathrm{G}$, so $\nu_{\mathrm{G}} = 2.8 \times 14 \approx 40\,\mathrm{MHz}$. This is the observed upper cutoff of the decametric emission.
- Frequency maps altitude: $B \propto r^{-3}$ puts 1 MHz at $\approx 3.4\,R_{\mathrm{J}}$ and 100 kHz at $\approx 7\,R_{\mathrm{J}}$.
- Low density: the high-latitude source region is almost empty, $n_{\mathrm{e}} \lesssim 1\,\mathrm{cm}^{-3}$ (order of magnitude), so $\nu_{\mathrm{p}} \lesssim 9\,\mathrm{kHz} \ll \nu_{\mathrm{G}}$. Condition 1 is met.

Jupiter and the ECM conditions: an inverted electron population



Electron distribution in momentum space.

- Electrons: keV to tens of keV, accelerated towards the pole (they also light the UV aurora).
- Pitch angles below $\sin^{-1}\sqrt{B_{\rm src}/B_{\rm atm}}$ ($\approx 9^\circ$ at $3.4\,R_{\rm J}$) hit the atmosphere: an empty loss cone, so $\partial f/\partial p_\perp > 0$.
- Juno measured such distributions (Louarn et al. 2017). Condition 2 is met.
- A 10 keV electron has $\gamma - 1 \approx 0.02$: emission a few per cent below $\nu_{\rm G}$. Condition 3 is met.

Comparing magnetically active emitters

Source	Band	Circular pol.	Coherent?	Interpretation
Earth (AKR)	$\sim$50–800 kHz	strong	yes	ECM
Jupiter: KOM to DAM	kHz–40 MHz	strong	yes	ECM
Solar microwave flare	1–20 GHz, broad	tens of %	no	gyrosynchrotron
Solar spike bursts	GHz, very narrow	high	yes	ECM candidate
Ultracool dwarfs	GHz, pulsed	$\sim$100%	yes	ECM, kG fields
M dwarfs (LOFAR)	120–170 MHz	high	mostly	ECM or plasma emission

- Ultracool dwarfs: periodic pulses (Hallinan et al. 2007, doi:10.1086/519790); radio and optical aurorae (Hallinan et al. 2015, doi:10.1038/nature14619).
- M dwarfs at 144 MHz: Callingham et al. 2021 (doi:10.1038/s41550-021-01483-0); possible star–planet interaction in GJ 1151: Vedantham et al. 2020 (doi:10.1038/s41550-020-1011-9).

Band edges are approximate; check the cited papers before quoting.

Is $T_{\rm b}$ alone enough? An ultracool-dwarf pulse

Illustrative pulse: $S_\nu = 1\,\mathrm{mJy}$ at 8 GHz from a dwarf at $d = 10\,\mathrm{pc}$.

$$T_{\rm b} = \frac{c^2 S_\nu}{2 k_{\rm B} \nu^2 \Omega_{\rm s}}, \qquad \Omega_{\rm s} = \pi R^2 / d^2$$

Assumed emitting radius R	$T_{\rm b}$ (K)
$R_{\rm J} = 7.1 \times 10^7$ m (whole disc)	3×10^9
$0.1\,R_{\rm J}$	3×10^{11}

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- With the whole disc, $T_{\rm b}$ is within reach of gyrosynchrotron emission from MeV electrons. $T_{\rm b}$ alone does not prove coherence here.
- The case for ECM rests on the $\sim$100% circular polarization, narrow band, and rotational periodicity together.
- Fundamental ECM at 8 GHz: $B \approx 2.9$ kG (1.4 kG if $s = 2$).

Worked example: magnetic fields from burst frequencies

$$B = \frac{\nu}{2.80\, s\ \mathrm{MHz}}\ \mathrm{G} \qquad (s = 1 \text{ or } 2)$$

Observed ν	Context	B ($s = 1$)	B ($s = 2$)
300 kHz	terrestrial AKR	0.11 G	0.05 G
40 MHz	Jovian DAM upper cutoff	14 G	7 G
150 MHz	M-dwarf burst (illustrative)	54 G	27 G
1.4 GHz	stellar burst (illustrative)	500 G	250 G
8.4 GHz	ultracool-dwarf pulse	3.0 kG	1.5 kG

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- Lower limit on the surface field: emission at ν requires $B \geq \nu/(2.8s\,\mathrm{MHz})$ somewhere; stronger fields may exist below the source.
- Harmonic number is an assumption: the factor of 2 is the main systematic (fundamental x-mode may be absorbed at the second-harmonic layer in dense coronae). Relativistic shifts are a few per cent.

Exoplanets: where would the emission be?

- ECM emission extends up to $\nu_{\max} \approx 2.8\,\mathrm{MHz}\,(B_{\mathrm{surface}}/\mathrm{G})$.
- Jupiter-like field ($\sim$10 G): tens of MHz. Earth-like field (< 1 G): $\lesssim$ few MHz, below the ionospheric cutoff ($\sim$10 MHz, Lecture 1).
- Expected flux at parsec distances is small and sporadic; searches use the lowest frequencies available (LOFAR, uGMRT, NenuFAR).

What a detection would give

- A lower limit on the planetary field strength (via $\nu_{\max}$).
- Evidence of a magnetosphere coupled to the stellar wind or host star.

Think about for the end of topic question

List every condition that must be met for us to *see* the emission.

Concept test

Question

Which observation most strongly favours a coherent magnetic burst: weak linear polarization over a broad band, or nearly 100% circular polarization in a narrow band?

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Answer: the narrow-band, $\sim$100% circularly polarized burst

1. Coherent cyclotron-maser emission is in one magnetoionic mode, so it can be almost fully circularly polarized.
2. It is emitted near the local ν_{G} and beamed, so it is narrow-band and episodic.

Summary

- $\nu_{\mathrm{G}} = 2.80\,\mathrm{MHz}\,(B/\mathrm{G})$ is the electron gyrofrequency. Low γ: emission at a few harmonics (cyclotron); $\gamma \sim 1$–3: a smooth gyrosynchrotron spectrum; $\gamma \gg 1$: synchrotron.
- Gyrosynchrotron is incoherent: $T_{\mathrm{b}} \lesssim E/k_{\mathrm{B}} \sim 10^9$–$10^{10}\,\mathrm{K}$, broad-band, with moderate circular polarization (flares, active stars).
- A maser needs a population inversion ($\tau_\nu < 0$): the radiation grows as $\mathrm{e}^{|\tau_\nu|}$, so T_{b} is limited by saturation, not by particle energy. A laser is brighter than filtered lamplight for the same reason.
- The electron-cyclotron maser needs $\nu_{\mathrm{p}} \ll \nu_{\mathrm{G}}$ and $\partial f/\partial p_\perp > 0$ (a loss cone or horseshoe). It gives narrow-band, beamed, $\sim$100% circularly polarized emission at $\nu \approx s\nu_{\mathrm{G}}$.
- Jupiter meets all three conditions: $B \approx 14\,\mathrm{G}$ gives the 40 MHz cutoff, the polar source region is nearly empty, and Juno saw loss-cone distributions. The frequency then gives a lower limit on B, with a factor-2 harmonic ambiguity; coherence is argued from T_{b}, polarization and structure together.

Further reading

- **Review:** ERA Ch. 2, “Radiation from an Accelerated Charge” and “Polarization”; ERA Ch. 5, “Magnetobremsstrahlung”.
- **Deepen:** TRA Ch. 10, cyclotron, gyrosynchrotron and coherent processes; TRA Ch. 11, Solar, stellar and planetary sources.
- **ECM theory:** Wu & Lee 1979 (doi:10.1086/157120); Melrose & Dulk 1982 (doi:10.1086/160219); Treumann 2006 (doi:10.1007/s00159-006-0001-y).
- **Jupiter:** Zarka 1998 (doi:10.1029/98JE01323); Louarn et al. 2017 (doi:10.1002/2017GL072923).
- **Stars:** Hallinan et al. 2007 (doi:10.1086/519790); Callingham et al. 2021 (doi:10.1038/s41550-021-01483-0).