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Axiom

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Axiom

An **axiom**, **postulate**, or **assumption** is a statement that is taken to be true, to serve as a premise or starting point for further reasoning and arguments. The word comes from the Ancient Greek word ἀξίωμα (*axíōma*), meaning 'that which is thought worthy or fit' or 'that which commends itself as evident'.[1][2]

The precise definition varies across fields of study. In classic philosophy, an axiom is a statement that is so evident or well-established, that it is accepted without controversy or question.[3] In modern logic, an axiom is a premise or starting point for reasoning.[4]

In mathematics, an *axiom* may be a "logical axiom" or a "non-logical axiom". Logical axioms are taken to be true within the system of logic they define and are often shown in symbolic form (e.g., (*A* and *B*) implies *A*), while non-logical axioms (e.g., $a + b = b + a$) are substantive assertions about the elements of the domain of a specific mathematical theory, such as arithmetic.

Non-logical axioms may also be called "postulates" or "assumptions". In most cases, a non-logical axiom is simply a formal logical expression used in deduction to build a mathematical theory, and might or might not be self-evident in nature (e.g., the parallel postulate in Euclidean geometry). To axiomatize a system of knowledge is to show that its claims can be derived from a small, well-understood set of sentences (the axioms), and there are typically many ways to axiomatize a given mathematical domain.

Any axiom is a statement that serves as a starting point from which other statements are logically derived. Whether it is meaningful (and, if so, what it means) for an axiom to be "true" is a subject of debate in the philosophy of mathematics.[5]

Etymology

The word *axiom* comes from the Greek word ἀξίωμα (*axíōma*), a verbal noun from the verb ἀξιόειν (*axioein*), meaning "to deem worthy", but also "to require", which in turn comes from ἄξιος (*áxios*), meaning "being in balance", and hence "having (the same) value (as)", "worthy", "proper". Among the ancient Greek philosophers an axiom was a claim which could be seen to be self-evidently true without any need for proof.[6]

The root meaning of the word *postulate* is to "demand"; for instance, Euclid demands that one agree that some things can be done (e.g., any two points can be joined by a straight line).[7]

Ancient geometers maintained some distinction between axioms and postulates. While commenting on Euclid's books, Proclus remarks that "Geminus held that this [4th] Postulate should not be classed as a postulate but as an axiom, since it does not, like the first three Postulates, assert the possibility of some construction but expresses an essential property."[8] Boethius translated 'postulate' as *petitio* and called the axioms *notiones communes* but in later manuscripts this usage was not always strictly kept.

Historical development

Early Greeks

The logico-deductive method whereby conclusions (new knowledge) follow from premises (old knowledge) through the application of sound arguments (syllogisms, rules of inference) was developed by the ancient Greeks, and has become the core principle of modern mathematics. Tautologies excluded, nothing can be deduced if nothing is assumed. Axioms and postulates are thus the basic assumptions underlying a given body of deductive knowledge. They are accepted without demonstration. All other assertions (theorems, in the case of mathematics) must be proven with the aid of these basic assumptions. However, the interpretation of mathematical knowledge has changed from ancient times to the modern, and consequently the terms *axiom* and *postulate* hold a slightly different meaning for the present day mathematician, than they did for Aristotle and Euclid.[6]

The ancient Greeks considered geometry as just one of several sciences, and held the theorems of geometry on par with scientific facts. As such, they developed and used the logico-deductive method as a means of avoiding error, and for structuring and communicating knowledge. Aristotle's posterior analytics is a definitive exposition of the classical view.

An "axiom", in classical terminology, referred to a self-evident assumption common to many branches of science. A good example would be the assertion that:

> When an equal amount is taken from equals, an equal amount results.

At the foundation of the various sciences lay certain additional hypotheses that were accepted without proof. Such a hypothesis was termed a *postulate*. While the axioms were common to many sciences, the postulates of each particular science were different. Their validity had to be established by means of real-world experience. Aristotle warns that the content of a science cannot be successfully communicated if the learner is in doubt about the truth of the postulates.[9]

The classical approach is well-illustrated[a] by Euclid's *Elements*, where a list of postulates is given (common-sensical geometric facts drawn from our experience), followed by a list of "common notions" (very basic, self-evident assertions).

Postulates

1. It is possible to draw a straight line from any point to any other point.
2. It is possible to extend a line segment continuously in both directions.
3. It is possible to describe a circle with any center and any radius.
4. It is true that all right angles are equal to one another.
5. ("Parallel postulate") It is true that, if a straight line falling on two straight lines make the interior angles on the same side less than two right angles, the two straight lines, if produced indefinitely, intersect on that side on which are the angles less than the two right angles.

Common notions

1. Things which are equal to the same thing are also equal to one another.
2. If equals are added to equals, the wholes are equal.
3. If equals are subtracted from equals, the remainders are equal.
4. Things which coincide with one another are equal to one another.

5. The whole is greater than the part.

Modern development

A lesson learned by mathematics in the last 150 years is that it is useful to strip the meaning away from the mathematical assertions (axioms, postulates, propositions, theorems) and definitions. One must concede the need for primitive notions, or undefined terms or concepts, in any study. Such abstraction or formalization makes mathematical knowledge more general, capable of multiple different meanings, and therefore useful in multiple contexts. Alessandro Padoa, Mario Pieri, and Giuseppe Peano were pioneers in this movement.

Structuralist mathematics goes further, and develops theories and axioms (e.g. field theory, group theory, topology, vector spaces) without *any* particular application in mind. The distinction between an "axiom" and a "postulate" disappears. The postulates of Euclid are profitably motivated by saying that they lead to a great wealth of geometric facts. The truth of these complicated facts rests on the acceptance of the basic hypotheses. However, by throwing out Euclid's fifth postulate, one can get theories that have meaning in wider contexts (e.g., hyperbolic geometry). As such, one must simply be prepared to use labels such as "line" and "parallel" with greater flexibility. The development of hyperbolic geometry taught mathematicians that it is useful to regard postulates as purely formal statements, and not as facts based on experience.

When mathematicians employ the field axioms, the intentions are even more abstract. The propositions of field theory do not concern any one particular application; the mathematician now works in complete abstraction. There are many examples of fields; field theory gives correct knowledge about them all.

It is not correct to say that the axioms of field theory are "propositions that are regarded as true without proof." Rather, the field axioms are a set of constraints. If any given system of addition and multiplication satisfies these constraints, then one is in a position to instantly know a great deal of extra information about this system.

Modern mathematics formalizes its foundations to such an extent that mathematical theories can be regarded as mathematical objects, and mathematics itself can be regarded as a branch of logic. Frege, Russell, Poincaré, Hilbert, and Gödel are some of the key figures in this development.

Another lesson learned in modern mathematics is to examine purported proofs carefully for hidden assumptions.

In the modern understanding, a set of axioms is any collection of formally stated assertions from which other formally stated assertions follow – by the application of certain well-defined rules. In this view, logic becomes just another formal system. A set of axioms should be consistent; it should be impossible to derive a contradiction from the axioms. A set of axioms should also be non-redundant; an assertion that can be deduced from other axioms need not be regarded as an axiom.

It was the early hope of modern logicians that various branches of mathematics, perhaps all of mathematics, could be derived from a consistent collection of basic axioms. An early success of the formalist program was Hilbert's formalization[b] of Euclidean geometry,[10] and the related demonstration of the consistency of those axioms.

In a wider context, there was an attempt to base all of mathematics on Cantor's set theory. Here, the emergence of Russell's paradox and similar antinomies of naïve set theory raised the possibility that any such system could turn out to be inconsistent.

The formalist project suffered a decisive setback, when in 1931 Gödel showed that it is possible, for any sufficiently large set of axioms (Peano's axioms, for example) to construct a statement whose truth is independent of that set of axioms. As a corollary, Gödel proved that the consistency of a theory like Peano arithmetic is an unprovable assertion within the scope of that theory.[11]

It is reasonable to believe in the consistency of Peano arithmetic because it is satisfied by the system of natural numbers, an infinite but intuitively accessible formal system. However, at present, there is no known way of demonstrating the consistency of the modern Zermelo–Fraenkel axioms for set theory. Furthermore, using techniques of forcing (Cohen) one can show that the continuum hypothesis (Cantor) is independent of the Zermelo–Fraenkel axioms.[12] Thus, even this very general set of axioms cannot be regarded as the definitive foundation for mathematics.

Other sciences

Experimental sciences - as opposed to mathematics and logic - also have general founding assertions from which a deductive reasoning can be built so as to express propositions that predict properties - either still general or much more specialized to a specific experimental context. For instance, Newton's laws in classical mechanics, Maxwell's equations in classical electromagnetism, Einstein's equation in general relativity, Mendel's laws of genetics, Darwin's Natural selection law, etc. These founding assertions are usually called *principles* or *postulates* so as to distinguish from mathematical *axioms*.

As a matter of facts, the role of axioms in mathematics and postulates in experimental sciences is different. In mathematics one neither "proves" nor "disproves" an axiom. A set of mathematical axioms gives a set of rules that fix a conceptual realm, in which the theorems logically follow. In contrast, in experimental sciences, a set of postulates shall allow deducing results that match or do not match experimental results. If postulates do not allow deducing experimental predictions, they do not set a scientific conceptual framework and have to be completed or made more accurate. If the postulates allow deducing predictions of experimental results, the comparison with experiments allows falsifying (falsified) the theory that the postulates install. A theory is considered valid as long as it has not been falsified.

Now, the transition between the mathematical axioms and scientific postulates is always slightly blurred, especially in physics. This is due to the heavy use of mathematical tools to support the physical theories. For instance, the introduction of Newton's laws rarely establishes as a prerequisite neither Euclidean geometry or differential calculus that they imply. It became more apparent when Albert Einstein first introduced special relativity where the invariant quantity is no more the Euclidean length l (defined as $l^2 = x^2 + y^2 + z^2$) > but the Minkowski spacetime interval s (defined as $s^2 = c^2t^2 - x^2 - y^2 - z^2$), and then general relativity where flat Minkowskian geometry is replaced with pseudo-Riemannian geometry on curved manifolds.

In quantum physics, two sets of postulates have coexisted for some time, which provide a very nice example of falsification. The 'Copenhagen school' (Niels Bohr, Werner Heisenberg, Max Born) developed an operational approach with a complete mathematical formalism that involves the description of quantum system by vectors ('states') in a separable Hilbert space, and physical quantities as linear operators that act in this Hilbert space. This approach is fully falsifiable and has so far produced the most accurate predictions in physics. But it has the unsatisfactory aspect of not allowing answers to questions one would naturally ask. For this reason, another 'hidden variables' approach was developed for some time by Albert Einstein, Erwin Schrödinger, David Bohm. It was created so as to try to give deterministic explanation to phenomena such as entanglement. This approach assumed that the Copenhagen school description was not complete, and postulated that some yet unknown variable was to be added to the theory so as to allow answering some of the questions it does not answer (the founding elements of which were discussed as the EPR paradox in 1935). Taking this ideas seriously, John Bell derived in 1964 a prediction that would lead to different experimental results (Bell's inequalities) in the Copenhagen and the Hidden variable case. The experiment was conducted first by Alain Aspect in the early 1980's, and the result excluded the simple hidden variable approach (sophisticated hidden variables could still exist but their properties would still be more disturbing than the problems they try to solve). This does not mean that the conceptual framework of quantum physics can be considered as complete now, since some open questions still exist (the limit between the quantum and classical realms, what happens during a quantum measurement, what happens in a completely closed quantum system such as the universe itself, etc.).

Mathematical logic

In the field of mathematical logic, a clear distinction is made between two notions of axioms: *logical* and *non-logical* (somewhat similar to the ancient distinction between "axioms" and "postulates" respectively).

Logical axioms

These are certain formulas in a formal language that are universally valid, that is, formulas that are satisfied by every assignment of values. Usually one takes as logical axioms *at least* some minimal set of tautologies that is sufficient for proving all tautologies in the language; in the case of predicate logic more logical axioms than that are required, in order to prove logical truths that are not tautologies in the strict sense.

Examples

Propositional logic

In propositional logic it is common to take as logical axioms all formulae of the following forms, where ϕ, χ, and ψ can be any formulae of the language and where the included primitive connectives are only "¬" for negation of the immediately following proposition and "→" for implication from antecedent to consequent propositions:

1. $\phi \to (\psi \to \phi)$
2. $(\phi \to (\psi \to \chi)) \to ((\phi \to \psi) \to (\phi \to \chi))$
3. $(\lnot\phi \to \lnot\psi) \to (\psi \to \phi)$.

Each of these patterns is an *axiom schema*, a rule for generating an infinite number of axioms. For example, if A, B, and C are propositional variables, then $A \to (B \to A)$ and $(A \to \lnot B) \to (C \to (A \to \lnot B))$ are both instances of axiom schema 1, and hence are axioms. It can be shown that with only these three axiom schemata and *modus ponens*, one can prove all tautologies of the propositional calculus. It can also be shown that no pair of these schemata is sufficient for proving all tautologies with *modus ponens*.

Other axiom schemata involving the same or different sets of primitive connectives can be alternatively constructed.[13]

These axiom schemata are also used in the predicate calculus, but additional logical axioms are needed to include a quantifier in the calculus.[14]

First-order logic

Axiom of Equality.
Let $\mathfrak{L}$ be a first-order language. For each variable x, the below formula is universally valid.

$x = x$

This means that, for any variable symbol x, the formula $x = x$ can be regarded as an axiom. Also, in this example, for this not to fall into vagueness and a never-ending series of "primitive notions", either a precise notion of what we mean by $x = x$ (or, for that matter, "to be equal") has to be well established first, or a purely formal and syntactical usage of the symbol $=$ has to be enforced, only regarding it as a string and only a string of symbols, and mathematical logic does indeed do that.

Another, more interesting example axiom scheme, is that which provides us with what is known as **Universal Instantiation**:

Axiom scheme for Universal Instantiation.
Given a formula ϕ in a first-order language $\mathfrak{L}$, a variable x and a term t that is substitutable for x in ϕ, the below formula is universally valid.

$\forall x\, \phi \to \phi^x_t$

Where the symbol ϕ^x_t stands for the formula ϕ with the term t substituted for x. (See Substitution of variables.) In informal terms, this example allows us to state that, if we know that a certain property P holds for every x and that t stands for a particular object in our structure, then we should be able to claim $P(t)$. Again, *we are claiming that the formula* $\forall x \phi \to \phi^x_t$ *is valid*, that is, we must be able to give a "proof" of this fact, or more properly speaking, a *metaproof*. These examples are *metatheorems* of our theory of mathematical logic since we are dealing with the very concept of *proof* itself. Aside from this, we can also have **Existential Generalization**:

Axiom scheme for Existential Generalization. Given a formula ϕ in a first-order language $\mathfrak{L}$, a variable x and a term t that is substitutable for x in ϕ, the below formula is universally valid.

$\phi^x_t \to \exists x\, \phi$

Non-logical axioms

Non-logical axioms are formulas that play the role of theory-specific assumptions. Reasoning about two different structures, for example, the natural numbers and the integers, may involve the same logical axioms; the non-logical axioms aim to capture what is special about a particular structure (or set of structures, such as groups). Thus non-logical axioms, unlike logical axioms, are not *tautologies*. Another name for a non-logical axiom is *postulate*.[15]

Almost every modern mathematical theory starts from a given set of non-logical axioms, and it was thought that, in principle, every theory could be axiomatized in this way and formalized down to the bare language of logical formulas.

Non-logical axioms are often simply referred to as *axioms* in mathematical discourse. This does not mean that it is claimed that they are true in some absolute sense. For example, in some groups, the group operation is commutative, and this can be asserted with the introduction of an additional axiom, but without this axiom, we can do quite well developing (the more general) group theory, and we can even take its negation as an axiom for the study of non-commutative groups.

Thus, an *axiom* is an elementary basis for a formal logic system that together with the rules of inference define a deductive system.

Examples

This section gives examples of mathematical theories that are developed entirely from a set of non-logical axioms (axioms, henceforth). A rigorous treatment of any of these topics begins with a specification of these axioms.

Basic theories, such as arithmetic, real analysis and complex analysis are often introduced non-axiomatically, but implicitly or explicitly there is generally an assumption that the axioms being used are the axioms of Zermelo–Fraenkel set theory with choice, abbreviated ZFC, or some very similar system of axiomatic set theory like Von Neumann–Bernays–Gödel set theory, a conservative extension of ZFC. Sometimes slightly stronger theories such as Morse–Kelley set theory or set theory with a strongly inaccessible cardinal allowing the use of a Grothendieck universe is used, but in fact, most mathematicians can actually prove all they need in systems weaker than ZFC, such as second-order arithmetic.

The study of topology in mathematics extends all over through point set topology, algebraic topology, differential topology, and all the related paraphernalia, such as homology theory, homotopy theory. The development of *abstract algebra* brought with itself group theory, rings, fields, and Galois theory.

This list could be expanded to include most fields of mathematics, including measure theory, ergodic theory, probability, representation theory, and differential geometry.

Arithmetic

The Peano axioms are the most widely used *axiomatization* of first-order arithmetic. They are a set of axioms strong enough to prove many important facts about number theory and they allowed Gödel to establish his famous second incompleteness theorem.[16]

We have a language $\mathfrak{L}_{NT} = \{0, S\}$ where 0 is a constant symbol and S is a unary function and the following axioms:

1. $\forall x. \neg(Sx = 0)$
2. $\forall x. \forall y. (Sx = Sy \to x = y)$
3. $(\phi(0) \land \forall x.\ (\phi(x) \to \phi(Sx))) \to \forall x. \phi(x)$ for any $\mathfrak{L}_{NT}$ formula ϕ with one free variable.

The standard structure is $\mathfrak{N} = \langle \mathbb{N}, 0, S \rangle$ where $\mathbb{N}$ is the set of natural numbers, S is the successor function and 0 is naturally interpreted as the number 0.

Euclidean geometry

Probably the oldest, and most famous, list of axioms are the 4 + 1 Euclid's postulates of plane geometry. The axioms are referred to as "4 + 1" because for nearly two millennia the fifth (parallel) postulate ("through a point outside a line there is exactly one parallel") was suspected of being derivable from the first four. Ultimately, the fifth postulate was found to be independent of the first four. One can assume that exactly one parallel through a point outside a line exists, or that infinitely many exist. This choice gives us two alternative forms of geometry in which the interior angles of a triangle add up to exactly 180 degrees or less, respectively, and are known as Euclidean and hyperbolic geometries. If one also removes the second postulate ("a line can be extended indefinitely") then elliptic geometry arises, where there is no parallel through a point outside a line, and in which the interior angles of a triangle add up to more than 180 degrees.

Real analysis

The objectives of the study are within the domain of real numbers. The real numbers are uniquely picked out (up to isomorphism) by the properties of a *Dedekind complete ordered field*, meaning that any nonempty set of real numbers with an upper bound has a least upper bound. However, expressing these properties as axioms requires the use of second-order logic. The Löwenheim–Skolem theorems tell us that if we restrict ourselves to first-order logic, any axiom system for the reals admits other models, including both models that are smaller than the reals and models that are larger. Some of the latter are studied in non-standard analysis.

Role in mathematical logic

Deductive systems and completeness

A **deductive system** consists of a set Λ of logical axioms, a set Σ of non-logical axioms, and a set $\{(\Gamma, \phi)\}$ of *rules of inference*. A desirable property of a deductive system is that it be **complete**. A system is said to be complete if, for all formulas ϕ,

$$\textbf{if } \Sigma \models \phi \textbf{ then } \Sigma \vdash \phi$$

that is, for any statement that is a *logical consequence* of Σ there actually exists a *deduction* of the statement from Σ. This is sometimes expressed as "everything that is true is provable", but it must be understood that "true" here means "made true by the set of axioms", and not, for example, "true in the intended interpretation". Gödel's completeness theorem establishes the completeness of a certain commonly used type of deductive system.

Note that "completeness" has a different meaning here than it does in the context of Gödel's first incompleteness theorem, which states that no *recursive, consistent* set of non-logical axioms Σ of the Theory of Arithmetic is *complete*, in the sense that there will always exist an arithmetic statement ϕ such that neither ϕ nor $\neg\phi$ can be proved from the given set of axioms.

There is thus, on the one hand, the notion of *completeness of a deductive system* and on the other hand that of *completeness of a set of non-logical axioms*. The completeness theorem and the incompleteness theorem, despite their names, do not contradict one another.

Further discussion

Early mathematicians regarded axiomatic geometry as a model of physical space, and obviously, there could only be one such model. The idea that alternative mathematical systems might exist was very troubling to mathematicians of the 19th century and the developers of systems such as Boolean algebra made elaborate efforts to derive them from traditional arithmetic. Galois showed just before his untimely death that these efforts were largely wasted. Ultimately, the abstract parallels between algebraic systems were seen to be more important than the details, and modern algebra was born. In the modern view, axioms may be any set of formulas, as long as they are not known to be inconsistent.

See also

Mathematics portal

Philosophy portal

- Axiomatic system
- Dogma
- First principle, axiom in science and philosophy
- List of axioms
- Model theory
- Regulæ Juris
- Theorem
- Presupposition
- Physical law
- Principle

Notes

a. Although not complete; some of the stated results did not actually follow from the stated postulates and common notions.

b. Hilbert also made explicit the assumptions that Euclid used in his proofs but did not list in his common notions and postulates.

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Further reading

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External links

- Axiom (https://philpapers.org/s/axiom) at PhilPapers
- Axiom (https://planetmath.org/Axiom) at PlanetMath.
- *Metamath* axioms page (http://us.metamath.org/mpegif/mmset.html#axioms)
- Axiom (https://axiomcan.com)

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Aurora

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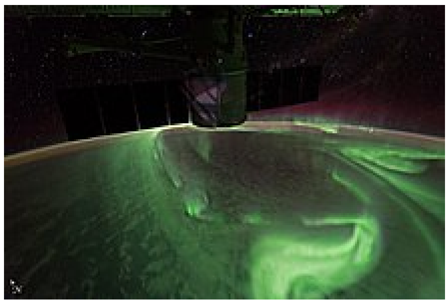
Aurora

Images of auroras from around the world, including those with rarer red and blue lights



Aurora australis seen from the ISS, 2017[1]

An **aurora**[a] (pl.: **aurorae** or **auroras**),[b] also commonly known as the **northern lights** (**aurora borealis**) or **southern lights** (**aurora australis**),[c] is a natural light display in Earth's sky, predominantly seen in high-latitude regions (around the Arctic and Antarctic). Auroras display dynamic patterns of brilliant lights that appear as curtains, rays, spirals, or dynamic flickers covering the entire sky.[3]

Auroras are the result of disturbances in the magnetosphere caused by the solar wind. Major disturbances result from enhancements in the speed of the solar wind from coronal holes and coronal mass ejections. These disturbances alter the trajectories of charged particles in the magnetospheric plasma. These particles, mainly electrons and protons, precipitate into the upper atmosphere (thermosphere/exosphere). The resulting ionization and excitation of atmospheric constituents emit light of varying colour and complexity. The form of the aurora, occurring within bands around both polar regions, is also dependent on the amount of acceleration imparted to the precipitating particles.

Most of the planets in the Solar System, some natural satellites, brown dwarfs, and even comets also host auroras.

Etymology

The word "**aurora**" is derived from the name of the Roman goddess of the dawn, Aurora, who travelled from east to west announcing the coming of the sun.[4] Ancient Greek poets used the corresponding name Eos metaphorically to refer to dawn, often mentioning its play of colors across the otherwise dark sky (*e.g.*, "rosy-fingered dawn").[5]

The words "**borealis**" and "**australis**" are derived from the names of the ancient gods of the north wind (Boreas) and the south wind (Auster) in Greek mythology.

Occurrence

Earth's atmosphere as it appears from space, as bands of different colours at the horizon. From the bottom, afterglow illuminates the troposphere in orange with silhouettes of clouds, and the stratosphere in white and blue. Next the mesosphere (pink area) extends to just below the edge of space at one hundred kilometers and the pink line of airglow of the lower thermosphere (dark), which hosts green and red **aurorae** over several hundred kilometers.

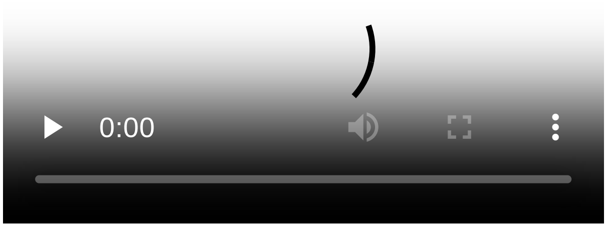
Most auroras occur in a band known as the "auroral zone",[6] which is typically 3° to 6° wide in latitude and between 10° and 20° from the geomagnetic poles at all local times (or longitudes), most clearly seen at night against a dark sky. A region that currently displays an aurora is called the "auroral oval", a band displaced by the solar wind towards the night side of Earth.[7] Early evidence for a geomagnetic connection comes from the statistics of auroral observations. Elias Loomis (1860),[8] and later Hermann Fritz (1881)[9] and Sophus Tromholt (1881)[10] in more detail, established that the aurora appeared mainly in the auroral zone.

In northern latitudes, the effect is known as the aurora borealis or the northern lights. The former term was coined by Galileo in 1619, from the Roman goddess of the dawn and the Greek name for the north wind.[11][12] The southern counterpart, the aurora australis or the southern lights, has features almost identical to the aurora borealis and changes simultaneously with changes in the northern auroral zone.[13] The aurora australis is visible from high southern latitudes in Antarctica, Chile, Argentina, South Africa, New Zealand and Australia. The aurora borealis is visible from areas around the Arctic such as Alaska, the Canadian Territories, Iceland, Greenland, Norway, Sweden, Finland, Scotland and Siberia. On rare occasions the aurora borealis can be seen as far south as the Mediterranean and the southern states of the US.

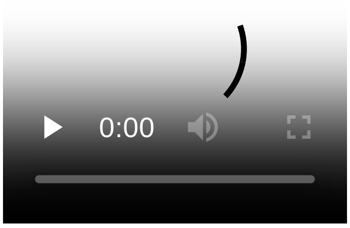
A geomagnetic storm causes the auroral ovals (north and south) to expand, bringing the aurora to lower latitudes. The instantaneous distribution of auroras ("auroral oval")[6] is slightly different, being centered about 3–5° nightward of the magnetic pole, so that auroral arcs reach furthest toward the equator when the magnetic pole in question is in between the observer and the Sun. The aurora can be seen best at this time, which is called magnetic midnight.

Auroras seen within the auroral oval may be directly overhead, but from farther away, they illuminate the poleward horizon as a greenish glow, or sometimes a faint red, as if the Sun were rising from an unusual direction. Auroras also occur poleward of the auroral zone as either diffuse patches or arcs,[14] which can be subvisual.

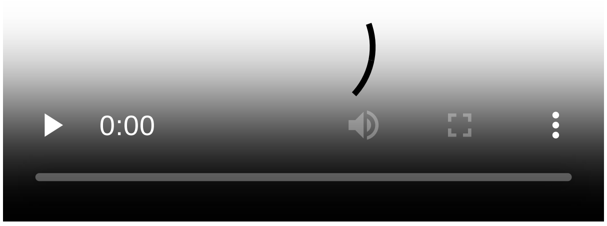
Videos of the aurora australis taken by the crew of Expedition 28 on board the International Space Station



This sequence of shots was taken 17 September 2011 from 17:22:27 to 17:45:12 GMT, on an ascending pass from south of Madagascar to just north of Australia over the Indian Ocean.

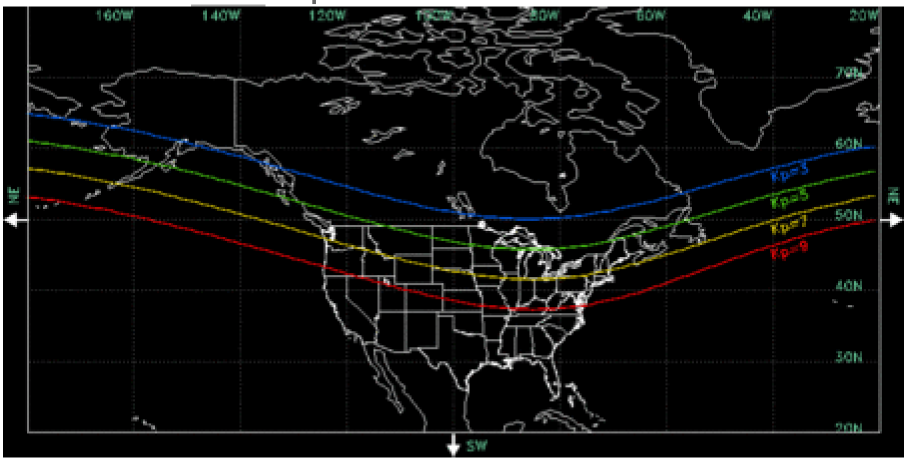


This sequence of shots was taken 7 September 2011 from 17:38:03 to 17:49:15 GMT, from the French Southern and Antarctic Lands in the South Indian Ocean to southern Australia.

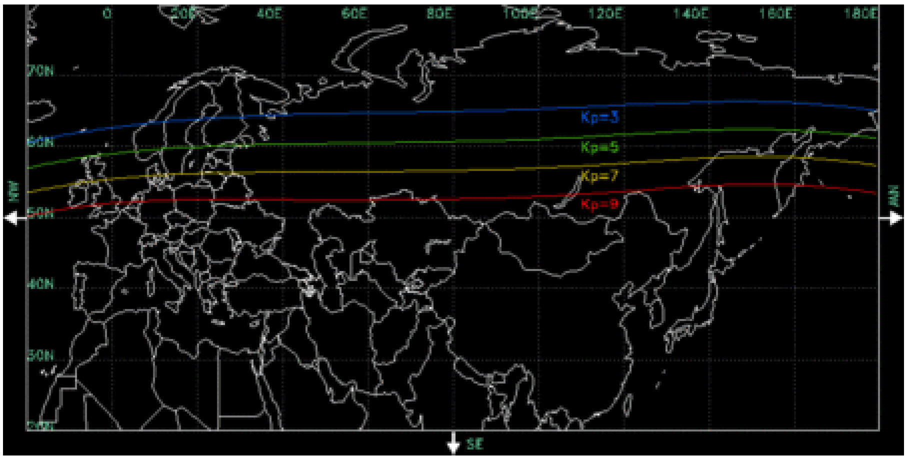


This sequence of shots was taken 11 September 2011 from 13:45:06 to 14:01:51 GMT, from a descending pass near eastern Australia, rounding about to an ascending pass to the east of New Zealand.

NOAA maps of North America and Eurasia



North America



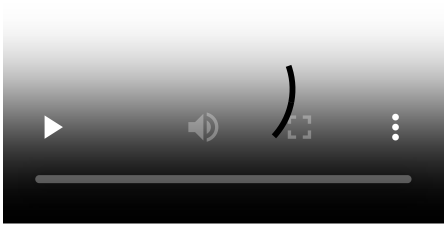
Eurasia

These maps show the local midnight equatorward boundary of the aurora at different levels of geomagnetic activity as of 28 October 2011 - these maps change as the location of the geomagnetic poles change. A *K*-index of K_p**=3** corresponds to relatively low levels of geomagnetic activity, while K_p**=9** represents high levels.

Auroras are occasionally seen in latitudes below the auroral zone, when a geomagnetic storm temporarily enlarges the auroral oval. Large geomagnetic storms are most common during the peak of the 11-year sunspot cycle or during the three years after the peak.[15][16] An electron spirals (gyrates) about a field line at an angle that is determined by its velocity vectors, parallel and perpendicular, respectively, to the local geomagnetic field vector B. This angle is known as the "pitch angle" of the particle. The distance, or radius, of the electron from the field line at any time is known as its Larmor radius. The pitch angle increases as the electron travels to a region of greater field strength nearer to the atmosphere. Thus, it is possible for some particles to return, or mirror, if the angle becomes 90° before entering the atmosphere to collide with the denser molecules there. Other particles that do not mirror enter the atmosphere and contribute to the auroral display over a range of altitudes. Other types of auroras have been observed from space; for example, "poleward arcs" stretching sunward across the polar cap, the related "theta aurora",[17] and "dayside arcs" near noon. These are relatively infrequent and poorly understood. Other interesting effects occur such as pulsating aurora, "black aurora" and their rarer companion "anti-black aurora" and subvisual red arcs. In addition to all these, a weak glow (often deep red) observed around the two polar cusps, the field lines separating the ones that close through Earth from those that are swept into the tail and close remotely.

Images

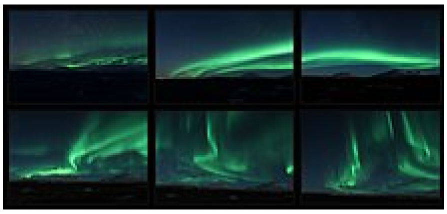
Early work on the imaging of the auroras was done in 1949 by the University of Saskatchewan using the SCR-270 radar. The altitudes where auroral emissions occur were revealed by Carl Størmer and his colleagues, who used cameras to triangulate more than 12,000 auroras.[18] They discovered that most of the light is produced between 90 and 150 km (56 and 93 mi) above the ground, while extending at times to more than 1,000 km (620 mi).



Video of the complete aurora australis by IMAGE, superimposed over a digital image of Earth

Forms

According to Clark (2007), there are four main forms that can be seen from the ground, from least to most visible:[19]



Different forms

- A mild *glow*, near the horizon. These can be close to the limit of visibility,[20] but can be distinguished from moonlit clouds because stars can be seen undiminished through the glow.
- *Patches* or *surfaces* that look like clouds.
- *Arcs* curve across the sky.
- *Rays* are light and dark stripes across arcs, reaching upwards by various amounts.
- *Coronas* cover much of the sky and diverge from one point on it.

Brekke (1994) also described some auroras as *curtains*.[21] The similarity to curtains is often enhanced by folds within the arcs. Arcs can fragment or break up into separate, at times rapidly changing, often rayed features that may fill the whole sky. These are also known as *discrete auroras*, which are at times bright enough to read a newspaper by at night.[22]

These forms are consistent with auroras being shaped by Earth's magnetic field. The appearances of arcs, rays, curtains, and coronas are determined by the shapes of the luminous parts of the atmosphere and a viewer's position.[23]

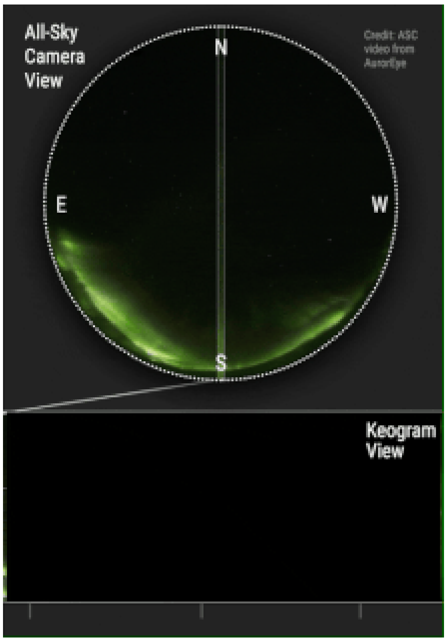
Colors and wavelengths of auroral light

- Red: At its highest altitudes, excited atomic oxygen emits at 630 nm (red); low concentration of atoms and lower sensitivity of eyes at this wavelength make this color visible only under more intense solar activity. The low number of oxygen atoms and their gradually diminishing concentration is responsible for the faint appearance of the top parts of the "curtains". Scarlet, crimson, and carmine are the most often-seen hues of red for the auroras.
- Green: At lower altitudes, the more frequent collisions suppress the 630 nm (red) mode: rather the 557.7 nm emission (green) dominates. A fairly high concentration of atomic oxygen and higher eye sensitivity in green make green auroras the most common. The excited molecular nitrogen (atomic nitrogen being rare due to the high stability of the N_2 molecule) plays a role here, as it can transfer energy by collision to an oxygen atom, which then radiates it away at the green wavelength. (Red and green can also mix together to produce pink or yellow hues.) The rapid decrease of concentration of atomic oxygen below about 100 km is responsible for the abrupt-looking end of the lower edges of the curtains. Both the 557.7 and 630.0 nm wavelengths correspond to forbidden transitions of atomic oxygen, a slow mechanism responsible for the graduality (0.7 s and 107 s respectively) of flaring and fading.

- Blue: At yet lower altitudes, atomic oxygen is uncommon, and molecular nitrogen and ionized molecular nitrogen take over in producing visible light emission, radiating at a large number of wavelengths in both red and blue parts of the spectrum, with 428 nm (blue) being dominant. Blue and purple emissions, typically at the lower edges of the "curtains", show up at the highest levels of solar activity.[24] The molecular nitrogen transitions are much faster than the atomic oxygen ones.
- Ultraviolet: Ultraviolet radiation from auroras (within the optical window but not visible to virtually all humans) has been observed with the requisite equipment. Ultraviolet auroras have also been seen on Mars,[25] Jupiter and Saturn.
- Infrared: Infrared radiation, in wavelengths that are within the optical window, is also part of many auroras.[25][26]
- Yellow and pink are a mix of red and green or blue. Other shades of red, as well as orange, may be seen on rare occasions; yellow-green is moderately common. As red, green, and blue are linearly independent colors, additive synthesis could, in theory, produce most human-perceived colors, but the ones mentioned in this article comprise a virtually exhaustive list.

Changes with time

Auroras change with time. Over the night, they begin with glows and progress towards coronas, although they may not reach them. They tend to fade in the opposite order.[21] Until about 1963 it was thought that these changes are due to the rotation of the Earth under a pattern fixed with respect to the Sun. Later it was found by comparing all-sky films of auroras from different places (collected during the International Geophysical Year) that they often undergo global changes in a process called auroral substorm. They change in a few minutes from quiet arcs all along the auroral oval to active displays along the darkside and after 1 – 3 hours they gradually change back.[27] Changes in auroras over time are commonly visualized using keograms.[28]



Construction of a keogram from one night's recording by an all-sky camera, 6/7 September 2021. Keograms are commonly used to visualize changes in aurorae over time.

At shorter time scales, auroras can change their appearances and intensity, sometimes so slowly as to be difficult to notice, and at other times rapidly down to the sub-second scale.[22] The phenomenon of pulsating auroras is an example of intensity variations over short timescales, typically with periods of 2–20 seconds. This type of aurora is generally accompanied by decreasing peak emission heights of about 8 km for blue and green emissions and above average solar wind speeds (~ 500 km/s).[29]

Other auroral radiation

In addition, the aurora and associated currents produce a strong radio emission around 150 kHz known as auroral kilometric radiation (AKR), discovered in 1972.[30] Ionospheric absorption makes AKR only observable from space. X-ray emissions, originating from the particles associated with auroras, have also been detected.[31]

Noise

Aurora noise, similar to a crackling noise, begins about 70 m (230 ft) above Earth's surface and is caused by charged particles in an inversion layer of the atmosphere formed during a cold night. The charged particles discharge when particles from the Sun hit the inversion layer, creating the noise.[32][33]

Unusual types

STEVE

In 2016, more than fifty citizen science observations described what was to them an unknown type of aurora which they named "STEVE", for "Strong Thermal Emission Velocity Enhancement". STEVE is not an aurora but is caused by a 25 km (16 mi) wide ribbon of hot plasma at an altitude of 450 km (280 mi), with a temperature of 6,000 K (5,730 °C; 10,340 °F) and flowing at a speed of 6 km/s (3.7 mi/s) (compared to 10 m/s (33 ft/s) outside the ribbon).[34]

Picket-fence aurora

The processes that cause STEVE are also associated with a picket-fence aurora, although the latter can be seen without STEVE.[35][36] It is an aurora because it is caused by precipitation of electrons in the atmosphere but it appears outside the auroral oval,[37] closer to the equator than typical auroras.[38] When the picket-fence aurora appears with STEVE, it is below.[36]

Dune aurora

First reported in 2020[39][40] and confirmed in 2021[41][42] the dune aurora phenomenon was discovered[43] by Finnish citizen scientists. It consists of regularly-spaced, parallel stripes of brighter emission in the green diffuse aurora which give the impression of sand dunes.[44] The phenomenon is believed to be caused by the modulation of atomic oxygen density by a large-scale atmospheric wave travelling horizontally in a waveguide through an inversion layer in the mesosphere in presence of electron precipitation.[41]

Horse-collar aurora

Horse-collar aurora (HCA) are auroral features in which the auroral ellipse shifts poleward during the dawn and dusk portions and the polar cap becomes teardrop-shaped. They form during periods when the interplanetary magnetic field (IMF) is permanently northward, when the IMF clock angle is small. Their formation is associated with the closure of the magnetic flux at the top of the dayside magnetosphere by the double lobe reconnection (DLR). There are approximately 8 HCA events per month, with no seasonal dependence, and that the IMF must be within 30 degrees of northwards.[45]

Conjugate auroras

Conjugate auroras are nearly exact mirror-image auroras found at conjugate points in the northern and southern hemispheres on the same geomagnetic field lines. These generally happen at the time of the equinoxes, when there is little difference in the orientation of the north and south geomagnetic poles to the sun. Attempts were made to image conjugate auroras by aircraft from Alaska and New Zealand in 1967, 1968, 1970, and 1971, with some success.[46]

Causes

A full understanding of the physical processes which lead to different types of auroras is still incomplete, but the basic cause involves the interaction of the solar wind with Earth's magnetosphere. The varying intensity of the solar wind produces effects of different magnitudes but includes one or more of the following physical scenarios.

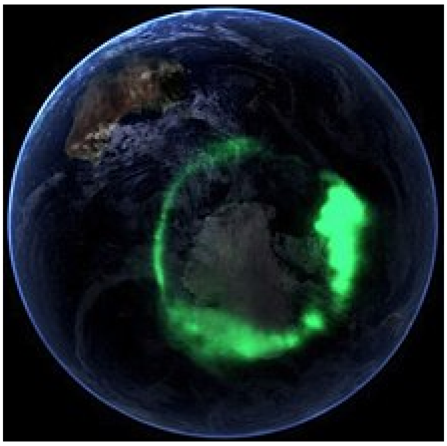
1. A quiescent solar wind flowing past Earth's magnetosphere steadily interacts with it and can both inject solar wind particles directly onto the geomagnetic field lines that are 'open', as opposed to being 'closed' in the opposite hemisphere, and provide diffusion through the bow shock. It can also cause particles already trapped in the radiation belts to precipitate into the atmosphere. Once particles are lost to the atmosphere from the radiation belts, under quiet conditions, new ones replace them only slowly, and the loss-cone becomes depleted. In the magnetotail, however, particle trajectories seem constantly to reshuffle, probably when the particles cross the very weak magnetic field near the equator. As a result, the flow of electrons in that region is nearly the same in all directions ("isotropic") and assures a steady supply of leaking electrons. The leakage of electrons does not leave the tail positively charged, because each leaked electron lost to the atmosphere is replaced by a low energy electron drawn upward from the ionosphere. Such replacement of "hot" electrons by "cold" ones is in complete accord with the second law of thermodynamics. The complete process, which also generates an electric ring current around Earth, is uncertain.
2. Geomagnetic disturbance from an enhanced solar wind causes distortions of the magnetotail ("magnetic substorms"). These 'substorms' tend to occur after prolonged spells (on the order of hours) during which the interplanetary magnetic field has had an appreciable southward component. This leads to a higher rate of interconnection between its field lines and those of Earth. As a result, the solar wind moves magnetic flux (tubes of magnetic field lines, 'locked' together with their resident plasma) from the day side of Earth to the magnetotail, widening the obstacle it presents to the solar wind flow and constricting the tail on the night-side. Ultimately some tail plasma can separate ("magnetic reconnection"); some blobs ("plasmoids") are squeezed downstream and are carried away with the solar wind; others are squeezed toward Earth where their motion feeds strong outbursts of auroras, mainly around midnight ("unloading process"). A geomagnetic storm resulting from greater interaction adds many more particles to the plasma trapped around Earth, also producing enhancement of the "ring current". Occasionally the resulting modification of Earth's magnetic field can be so strong that it produces auroras visible at middle latitudes, on field lines much closer to the equator than those of the auroral zone.

3. Acceleration of auroral charged particles invariably accompanies a magnetospheric disturbance that causes an aurora. This mechanism, which is believed to predominantly arise from strong electric fields along the magnetic field or wave-particle interactions, raises

the velocity of a particle in the direction of the guiding magnetic field. The pitch angle is thereby decreased and increases the chance of it being precipitated into the atmosphere. Both electromagnetic and electrostatic waves, produced at the time of greater geomagnetic disturbances, make a significant contribution to the energizing processes that sustain an aurora. Particle acceleration provides a complex intermediate process for transferring energy from the solar wind indirectly into the atmosphere.


Moon and aurora

The details of these phenomena are not fully understood. However, it is clear that the prime source of auroral particles is the solar wind feeding the magnetosphere, the reservoir containing the radiation zones and temporarily magnetically trapped particles confined by the geomagnetic field, coupled with particle acceleration processes.[47]


Aurora australis (11 September 2005) as captured by NASA's IMAGE satellite, digitally overlaid onto *The Blue Marble* composite image. An animation created using the same satellite data is also available.

Auroral particles

The immediate cause of the ionization and excitation of atmospheric constituents leading to auroral emissions was discovered in 1960, when a pioneering rocket flight from Fort Churchill in Canada revealed a flux of electrons entering the atmosphere from above.[48] Since then an extensive collection of measurements has been acquired painstakingly and with steadily improving resolution since the 1960s by many research teams using rockets and satellites to traverse the auroral zone. The main findings have been that auroral arcs and other bright forms are due to electrons that have been accelerated during the final few 10,000 km or so of their plunge into the atmosphere.[49] These electrons often, but not always, exhibit a peak in their energy distribution, and are preferentially aligned along the local direction of the magnetic field.

Electrons mainly responsible for diffuse and pulsating auroras have, in contrast, a smoothly falling energy distribution, and an angular (pitch-angle) distribution favouring directions perpendicular to the local magnetic field. Pulsations were discovered to originate at or close to the equatorial crossing point of auroral zone magnetic field lines.[50] Protons are also associated with auroras, both discrete and diffuse.

Atmosphere

Auroras result from emissions of photons in Earth's upper atmosphere, above 80 km (50 mi), from ionized nitrogen atoms regaining an electron, and oxygen atoms and nitrogen based molecules returning from an excited state to ground state.[51] They are ionized or excited by the collision of particles precipitated into the atmosphere. Both incoming electrons and protons may be involved. Excitation energy is lost within the atmosphere by the emission of a photon, or by collision with another atom or molecule:

Oxygen emissions
: green or orange-red, depending on the amount of energy absorbed.

Nitrogen emissions

blue, purple or red; blue and purple if the molecule regains an electron after it has been ionized, red if returning to ground state from an excited state.

Oxygen is unusual in terms of its return to ground state: it can take 0.7 seconds to emit the 557.7 nm green light and up to two minutes for the red 630.0 nm emission. Collisions with other atoms or molecules absorb the excitation energy and prevent emission, this process is called collisional quenching. Because the highest parts of the atmosphere contain a higher percentage of oxygen and lower particle densities, such collisions are rare enough to allow time for oxygen to emit red light. Collisions become more frequent progressing down into the atmosphere due to increasing density, so that red emissions do not have time to happen, and eventually, even green light emissions are prevented.

This is why there is a color differential with altitude; at high altitudes oxygen red dominates, then oxygen green and nitrogen blue/purple/red, then finally nitrogen blue/purple/red when collisions prevent oxygen from emitting anything. Green is the most common color. Then comes pink, a mixture of light green and red, followed by pure red, then yellow (a mixture of red and green), and finally, pure blue.

Precipitating protons generally produce optical emissions as incident hydrogen atoms after gaining electrons from the atmosphere. Proton auroras are usually observed at lower latitudes.[52]

Ionosphere

Bright auroras are generally associated with Birkeland currents (Schield et al., 1969;[53] Zmuda and Armstrong, 1973[54]), which flow down into the ionosphere on one side of the pole and out on the other. In between, some of the current connects directly through the ionospheric E layer (125 km); the rest ("region 2") detours, leaving again through field lines closer to the equator and closing through the "partial ring current" carried by magnetically trapped plasma. The ionosphere is an ohmic conductor, so some consider that such currents require a driving voltage, which an, as yet unspecified, dynamo mechanism can supply. Electric field probes in orbit above the polar cap suggest voltages of the order of 40,000 volts, rising up to more than 200,000 volts during intense magnetic storms. In another interpretation, the currents are the direct result of electron acceleration into the atmosphere by wave/particle interactions.

Ionospheric resistance has a complex nature, and leads to a secondary Hall current flow. By a strange twist of physics, the magnetic disturbance on the ground due to the main current almost cancels out, so most of the observed effect of auroras is due to a secondary current, the auroral electrojet. An auroral electrojet index (measured in nanotesla) is regularly derived from ground data and serves as a general measure of auroral activity. Kristian Birkeland[55] deduced that the currents flowed in the east–west directions along the auroral arc, and such currents, flowing from the dayside toward (approximately) midnight were later named "auroral electrojets" (see also Birkeland currents). Ionosphere can contribute to the formation of auroral arcs via the feedback instability under high ionospheric resistance conditions, observed at night time and in dark Winter hemisphere.[56]

Interaction of the solar wind with Earth

Earth is constantly immersed in the solar wind, a flow of magnetized hot plasma (a gas of free electrons and positive ions) emitted by the Sun in all directions, a result of the two-million-degree temperature of the Sun's outermost layer, the corona. The solar wind reaches Earth with a velocity typically around 400 km/s, a density of around 5 ions/cm^3 and a magnetic field intensity of around 2–5 nT (for comparison, Earth's surface field is typically 30,000–50,000 nT). During magnetic storms, in particular, flows can be several times faster; the interplanetary magnetic field (IMF) may also be much stronger. Joan Feynman deduced in the 1970s that the long-term averages of solar wind speed correlated with geomagnetic activity.[57] Her work resulted from data collected by the Explorer 33 spacecraft.

The solar wind and magnetosphere consist of plasma (ionized gas), which conducts electricity. It is well known (since Michael Faraday's work around 1830) that when an electrical conductor is placed within a magnetic field while relative motion occurs in a direction that the conductor cuts *across* (or is cut *by*), rather than *along*, the lines of the magnetic field, an electric current is induced within the conductor. The strength of the current depends on a) the rate of relative motion, b) the strength of the magnetic field, c) the number of conductors ganged together and d) the distance between the conductor and the magnetic field, while the *direction* of flow is dependent upon the direction of relative motion. Dynamos make use of this basic process ("the dynamo effect"), any and all conductors, solid or otherwise are so affected, including plasmas and other fluids.

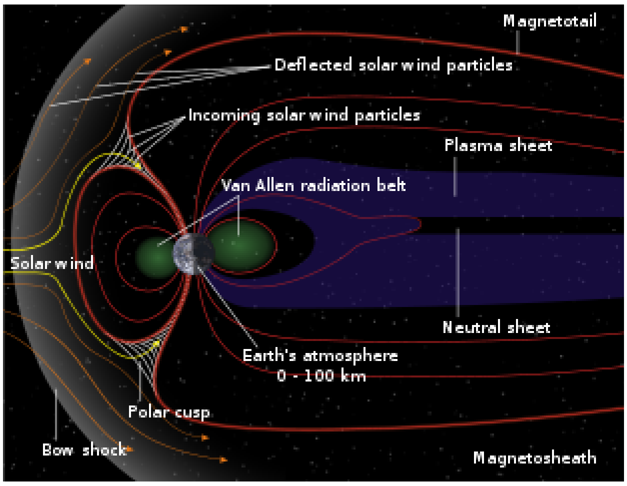
The IMF originates on the Sun, linked to the sunspots, and its field lines (lines of force) are dragged out by the solar wind. That alone would tend to line them up in the Sun-Earth direction, but the rotation of the Sun angles them at Earth by about 45 degrees forming a spiral in the ecliptic plane, known as the Parker spiral. The field lines passing Earth are therefore usually linked to those near the western edge ("limb") of the visible Sun at any time.[58]

The solar wind and the magnetosphere, being two electrically conducting fluids in relative motion, should be able in principle to generate electric currents by dynamo action and impart energy from the flow of the solar wind. However, this process is hampered by the fact that plasmas conduct readily along magnetic field lines, but less readily perpendicular to them. Energy is more effectively transferred by the temporary magnetic connection between the field lines of the solar wind and those of the magnetosphere. Unsurprisingly this process is known as magnetic reconnection. As already mentioned, it happens most readily when the interplanetary field is directed southward, in a similar direction to the geomagnetic field in the inner regions of both the north magnetic pole and south magnetic pole.

Auroras are more frequent and brighter during the intense phase of the solar cycle when coronal mass ejections increase the intensity of the solar wind.[59]

Magnetosphere

Earth's magnetosphere is shaped by the impact of the solar wind on Earth's magnetic field. This forms an obstacle to the flow, diverting it, at an average distance of about 70,000 km (11 Earth radii or Re),[60] producing a bow shock 12,000 km to 15,000 km (1.9 to 2.4 Re) further upstream. The width of the magnetosphere abreast of Earth is typically 190,000 km (30 Re), and on the night side a long "magnetotail" of stretched field lines extends to great distances (> 200 Re).



Schematic of Earth's magnetosphere

The high latitude magnetosphere is filled with plasma as the solar wind passes Earth. The flow of plasma into the magnetosphere increases with additional turbulence, density, and speed in the solar wind. This flow is favored by a southward component of the IMF, which can then directly connect to the high latitude geomagnetic field lines.[61] The flow pattern of magnetospheric plasma is mainly from the magnetotail toward Earth, around Earth and back into the solar wind through the magnetopause on the day-side. In addition to moving perpendicular to Earth's magnetic field, some magnetospheric plasma travels down along Earth's magnetic field lines, gains additional energy and loses it to the atmosphere in the auroral zones. The cusps of the magnetosphere, separating geomagnetic field lines that close through Earth from those that close remotely allow a small amount of solar wind to directly reach the top of the atmosphere, producing an auroral glow.

On 26 February 2008, THEMIS probes were able to determine, for the first time, the triggering event for the onset of magnetospheric substorms.[62] Two of the five probes, positioned approximately one third the distance to the Moon, measured events suggesting a magnetic reconnection event 96 seconds prior to auroral intensification.[63]

Geomagnetic storms that ignite auroras may occur more often during the months around the equinoxes. It is not well understood, but geomagnetic storms may vary with Earth's seasons. Two factors to consider are the tilt of both the solar and Earth's axis to the ecliptic plane. As Earth orbits throughout a year, it experiences an interplanetary magnetic field (IMF) from different latitudes of the Sun, which is tilted at 8 degrees. Similarly, the 23-degree tilt of Earth's axis about which the geomagnetic pole rotates with a diurnal variation changes the daily average angle that the geomagnetic field presents to the incident IMF throughout a year. These factors combined can lead to minor cyclical changes in the detailed way that the IMF links to the magnetosphere. In turn, this affects the average probability of opening a door through which energy from the solar wind can reach Earth's inner magnetosphere and thereby enhance auroras. Recent evidence in 2021 has shown that individual separate substorms may in fact be correlated networked communities.[64]

Auroral particle acceleration

Just as there are many types of aurora, there are many different mechanisms that accelerate auroral particles into the atmosphere. Electron aurora in Earth's auroral zone (i.e. commonly visible aurora) can be split into two main categories with different immediate causes: diffuse and discrete aurora. Diffuse aurora appear relatively structureless to an observer on the ground, with indistinct edges and amorphous forms. Discrete aurora are structured into distinct features with well-defined edges such as arcs, rays and coronas; they also tend to be much brighter than the diffuse aurora.

In both cases, the electrons that eventually cause the aurora start out as electrons trapped by the magnetic field in Earth's magnetosphere. These trapped particles bounce back and forth along magnetic field lines and are prevented from hitting the atmosphere by the magnetic mirror formed by the increasing magnetic field strength closer to Earth. The magnetic mirror's ability to trap a particle depends on the particle's pitch angle: the angle between its direction of motion and the local magnetic field. An aurora is created by processes that decrease the pitch angle of many individual electrons, freeing them from the magnetic trap and causing them to hit the atmosphere.

In the case of diffuse auroras, the electron pitch angles are altered by their interaction with various plasma waves. Each interaction is essentially wave-particle scattering; the electron energy after interacting with the wave is similar to its energy before interaction, but the direction of motion is altered. If the final direction of motion after scattering is close to the field line (specifically, if it falls within the loss cone) then the electron will hit the atmosphere. Diffuse auroras are caused by the collective effect of many such scattered electrons hitting the atmosphere. The process is mediated by the plasma waves, which become stronger during periods of high geomagnetic activity, leading to increased diffuse aurora at those times.

In the case of discrete auroras, the trapped electrons are accelerated toward Earth by electric fields that form at an altitude of about 4000–12000 km in the "auroral acceleration region". The electric fields point away from Earth (i.e. upward) along the magnetic field line.[65] Electrons moving downward through these fields gain a substantial amount of energy (on the order of a few keV) in the direction along the magnetic field line toward Earth. This field-aligned acceleration decreases the pitch angle for all of the electrons passing through the region, causing many of them to hit the upper atmosphere. In contrast to the scattering process leading to diffuse auroras, the electric field increases the kinetic energy of all of the electrons transiting downward through the acceleration region by the same amount. This accelerates electrons starting from the magnetosphere with initially low energies (tens of eV or less) to energies required to create an aurora (100s of eV or greater), allowing that large source of particles to contribute to creating auroral light.

The accelerated electrons carry an electric current along the magnetic field lines (a Birkeland current). Since the electric field points in the same direction as the current, there is a net conversion of electromagnetic energy into particle energy in the auroral acceleration region (an electric load). The energy to power this load is eventually supplied by the magnetized solar wind flowing around the obstacle of Earth's magnetic field, although exactly how that power flows through the magnetosphere is still an active area of research.[66] While the energy to power the aurora is ultimately derived from the solar wind, the electrons themselves do not travel directly from the solar wind into Earth's auroral zone; magnetic field lines from these regions do not connect to the solar wind, so there is no direct access for solar wind electrons.

Some auroral features are also created by electrons accelerated by dispersive Alfvén waves. At small wavelengths transverse to the background magnetic field (comparable to the electron inertial length or ion gyroradius), Alfvén waves develop a significant electric field parallel to the background magnetic field. This electric field can accelerate electrons to keV energies, significant to produce auroral arcs.[67] If the electrons have a speed close to that of the wave's phase velocity, they are accelerated in a manner analogous to a surfer catching an ocean wave.[68][69] This constantly-changing wave electric field can accelerate electrons along the field line, causing some of them to hit the atmosphere. Electrons accelerated by this mechanism tend to have a broad energy spectrum, in contrast to the sharply-peaked energy spectrum typical of electrons accelerated by quasi-static electric fields.

In addition to the discrete and diffuse electron aurora, proton aurora is caused when magnetospheric protons collide with the upper atmosphere. The proton gains an electron in the interaction, and the resulting neutral hydrogen atom emits photons. The resulting light is too dim to be seen with the naked eye. Other aurora not covered by the above discussion include transpolar arcs (formed poleward of the auroral zone), cusp aurora (formed in two small high-latitude areas on the dayside) and some non-terrestrial auroras.

Historically significant events

The discovery of a 1770 Japanese diary in 2017 depicting auroras above the ancient Japanese capital of Kyoto suggested that the storm may have been 7% larger than the Carrington event, which affected telegraph networks.[70][71]

The auroras that resulted from the "great geomagnetic storm" on both 28 August and 2 September 1859, however, are thought to be the most spectacular in recent recorded history. In a paper to the Royal Society on 21 November 1861, Balfour Stewart described both auroral events as documented by a self-recording magnetograph at the Kew Observatory and established the connection between the 2 September 1859 auroral storm and the Carrington–Hodgson flare event when he observed that "It is not impossible to suppose that in this case our luminary was taken *in the act*."[72] The second auroral event, which occurred on 2 September 1859, was a result of the (unseen) coronal mass ejection associated with the exceptionally intense Carrington–Hodgson white light solar flare on 1 September 1859. This event produced auroras so widespread and extraordinarily bright that they were seen and reported in published scientific measurements, ship logs, and newspapers throughout the United States, Europe, Japan, and Australia. It was reported by *The New York Times* that in Boston on Friday 2 September 1859 the aurora was "so brilliant that at about one o'clock ordinary print could be read by the light".[73] One o'clock EST time on Friday 2 September would have been 6:00 GMT; the self-recording magnetograph at the Kew Observatory was recording the geomagnetic storm, which was then one hour old, at its full intensity. Between 1859 and 1862, Elias Loomis published a series of nine papers on the Great Auroral Exhibition of 1859 in the *American Journal of Science* where he collected worldwide reports of the auroral event.[8]

That aurora is thought to have been produced by one of the most intense coronal mass ejections in history. It is also notable for the fact that it is the first time where the phenomena of auroral activity and electricity were unambiguously linked. This insight was made possible not only due to scientific magnetometer measurements of the era, but also as a result of a significant portion of the 125,000 miles (201,000 km) of telegraph lines then in service being significantly disrupted for many hours throughout the storm. Some telegraph lines, however, seem to have been of the appropriate length and orientation to produce a sufficient geomagnetically induced current from the electromagnetic field to allow for continued communication with the telegraph operator power supplies switched off.[74] The following conversation occurred between two operators of the American Telegraph Line between Boston and Portland, Maine, on the night of 2 September 1859 and reported in the *Boston Traveler*:

> *Boston operator (to Portland operator):* "Please cut off your battery [power source] entirely for fifteen minutes."
> *Portland operator:* "Will do so. It is now disconnected."
> *Boston:* "Mine is disconnected, and we are working with the auroral current. How do you receive my writing?"
> *Portland:* "Better than with our batteries on. – Current comes and goes gradually."
> *Boston:* "My current is very strong at times, and we can work better without the batteries, as the aurora seems to neutralize and augment our batteries alternately, making current too strong at times for our relay magnets. Suppose we work without batteries while we are affected by this trouble."
> *Portland:* "Very well. Shall I go ahead with business?"
> *Boston:* "Yes. Go ahead."

The conversation was carried on for around two hours using no battery power at all and working solely with the current induced by the aurora, and it was said that this was the first time on record that more than a word or two was transmitted in such manner.[73] Such events led to the general conclusion that

> The effect of the Aurora on the electric telegraph is generally to increase or diminish the electric current generated in working the wires. Sometimes it entirely neutralizes them, so that, in effect, no fluid [current] is discoverable in them. The aurora borealis seems to be composed of a mass of electric matter, resembling in every respect, that generated by the electric galvanic battery. The currents from it change coming on the wires, and then disappear: the mass of the aurora rolls from the horizon to the zenith.[75]

Historical views and folklore

The earliest datable record of an aurora was recorded in the *Bamboo Annals*, a historical chronicle of the history of ancient China, in 977 or 957 BC.[76] An aurora was described by the Greek explorer Pytheas in the 4th century BC.[77] Seneca wrote about auroras in the first book of his *Naturales Quaestiones*, classifying them, for instance, as *pithaei* ('barrel-like'); *chasmata* ('chasm'); *pogoniae* ('bearded'); *cyparissae* ('like cypress trees'); and describing their manifold colors. He wrote about whether they were above or below the clouds, and recalled that under Tiberius, an aurora formed above the port city of Ostia that was so intense and red that a cohort of the army, stationed nearby for fire duty, galloped to the rescue.[78] It has been suggested that Pliny the Elder depicted the aurora borealis in his *Natural History*, when he refers to *trabes*, *chasma*, 'falling red flames', and 'daylight in the night'.[79]

The earliest depiction of the aurora may have been a Cro-Magnon cave painting dated to 30,000 BC.[80]

The oldest known written record of the aurora was in a Chinese legend written around 2600 BC. On an autumn around 2000 BC,[80] according to a legend, a young woman named Fubao was sitting alone in the wilderness by a bay, when suddenly a "magical band of light" appeared like "moving clouds and flowing water", turning into a bright halo around the Big Dipper, which cascaded a pale silver brilliance, illuminating the earth and making shapes and shadows seem alive. Moved by this sight, Fubao became pregnant and gave birth to a son, the Emperor Xuanyuan, known legendarily as the initiator of Chinese culture and the ancestor of all Chinese people. In the *Shanhaijing*, a creature named *Shilong* is described to be like a red dragon shining in the night sky with a body a thousand miles long. In ancient times, the Chinese did not have a fixed word for the aurora, so it was named according to the different shapes of the aurora, such as "Sky Dog" (天狗), "Sword/Knife Star" (刀星), "Chiyou banner" (蚩尤旗), "Sky's Open Eyes" (天开眼), and "Stars like Rain" (星陨如雨).

In Japanese folklore, pheasants were considered messengers from heaven. However, researchers from Japan's Graduate University for Advanced Studies and National Institute of Polar Research claimed in March 2020 that red pheasant tails witnessed across the night sky over Japan in 620 A.D., might be a red aurora produced during a magnetic storm.[81]

In the traditions of Aboriginal Australians, the Aurora Australis is commonly associated with fire. For example, the Gunditjmara people of western Victoria called auroras *puae buae* ('ashes'), while the Gunai people of eastern Victoria perceived auroras as bushfires in the spirit world. The Dieri people of South Australia say that an auroral display is *kootchee*, an evil spirit creating a large fire. Similarly, the Ngarrindjeri people of South Australia refer to auroras seen over Kangaroo Island as the campfires of spirits in the 'Land of the Dead'. Aboriginal people in southwest Queensland believe the auroras to be the fires of the *Oola Pikka*, ghostly spirits who spoke to the people through auroras. Sacred law forbade anyone except male elders from watching or interpreting the messages of ancestors they believed were transmitted through an aurora.[82]

The Aboriginal Australians associated auroras (which are mainly low on the horizon and predominantly red) with fire.

Among the Māori people of New Zealand, aurora australis or *Tahunui-a-rangi* ("great torches in the sky") were alight by ancestors who sailed south to a "land of ice" (or their descendants);[83][84] these people were said to be Ui-te-Rangiora's expedition party who had reached the Southern Ocean.[83] around the 7th century.[85]

In Scandinavia, the first mention of *norðrljós* (the northern lights) is found in the Norwegian chronicle *Konungs Skuggsjá* from AD 1230. The chronicler has heard about this phenomenon from compatriots returning from Greenland, and he gives three possible explanations: that the ocean was surrounded by vast fires; that the sun flares could reach around the world to its night side; or that glaciers could store energy so that they eventually became fluorescent.[86]

Walter William Bryant wrote in his book *Kepler* (1920) that Tycho Brahe "seems to have been something of a homœopathist, for he recommends sulfur to cure infectious diseases 'brought on by the sulphurous vapours of the Aurora Borealis' ".[87]

In 1778, Benjamin Franklin theorized in his paper *Aurora Borealis, Suppositions and Conjectures towards forming an Hypothesis for its Explanation* that an aurora was caused by a concentration of electrical charge in the polar regions intensified by the snow and moisture in the air:[88][89][90]

Aurora pictured as wreath of rays in the coat of arms of Utsjoki

> May not then the great quantity of electricity brought into the polar regions by the clouds, which are condens'd there, and fall in snow, which electricity would enter the earth, but cannot penetrate the ice; may it not, I say (as a bottle overcharged) break thro' that low atmosphere and run along in the vacuum over the air towards the equator, diverging as the degrees of longitude enlarge, strongly visible where densest, and becoming less visible as it more diverges; till it finds a passage to the earth in more temperate climates, or is mingled with the upper air?

Observations of the rhythmic movement of compass needles due to the influence of an aurora were confirmed in the Swedish city of Uppsala by Anders Celsius and Olof Hiorter. In 1741, Hiorter was able to link large magnetic fluctuations with an aurora being observed overhead. This evidence helped to support their theory that 'magnetic storms' are responsible for such compass fluctuations.[91]

A variety of Native American myths surround the spectacle. The European explorer Samuel Hearne traveled with Chipewyan Dene in 1771 and recorded their views on the *ed-thin* ('caribou'). According to Hearne, the Dene people saw the resemblance between an aurora and the sparks produced when caribou fur is stroked. They believed that the lights were the spirits of their departed friends dancing in the sky, and when they shone brightly it meant that their deceased friends were very happy.[92]

Church's 1865 painting *Aurora Borealis*

During the night after the Battle of Fredericksburg, an aurora was seen from the battlefield. The Confederate Army took this as a sign that God was on their side, as the lights were rarely seen so far south. The painting *Aurora Borealis* by Frederic Edwin Church is widely interpreted to represent the conflict of the American Civil War.[93]

A mid 19th-century British source says auroras were a rare occurrence before the 18th century.[94] It quotes Halley as saying that before the aurora of 1716, no such phenomenon had been recorded for more than 80 years, and none of any consequence since 1574. It says no appearance is recorded in the *Transactions of the French Academy of Sciences* between 1666 and 1716; and that one aurora recorded in *Berlin Miscellany* for 1797 was called a very rare event. One observed in 1723 at Bologna was stated to be the first ever seen there. Celsius (1733) states the oldest residents of Uppsala thought the phenomenon a great rarity before 1716. The period between approximately 1645 and 1715 corresponds to the Maunder minimum in sunspot activity.

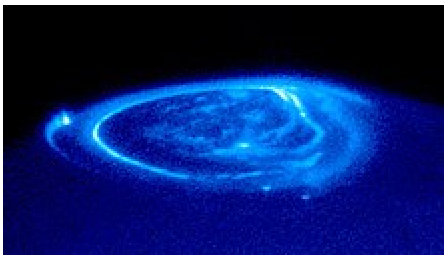
In Robert W. Service's satirical poem "The Ballad of the Northern Lights" (1908), a Yukon prospector discovers that the aurora is the glow from a radium mine. He stakes his claim, then goes to town looking for investors.

In the early 1900s, the Norwegian scientist Kristian Birkeland laid the foundation for current understanding of geomagnetism and polar auroras.

In Sami mythology, the northern lights are caused by the deceased who bled to death cutting themselves, their blood spilling on the sky. Many aboriginal peoples of northern Eurasia and North America share similar beliefs of northern lights being the blood of the deceased, some believing they are caused by dead warriors' blood spraying on the sky as they engage in playing games, riding horses or having fun in some other way.

On other planets

Both Jupiter and Saturn have magnetic fields that are stronger than Earth's (Jupiter's equatorial field strength is 4.3 gauss, compared to 0.3 gauss for Earth), and both have extensive radiation belts. Auroras have been observed on both gas planets, most clearly using the Hubble Space Telescope, and the *Cassini* and *Galileo* spacecraft, as well as on Uranus and Neptune.[95]



Jupiter aurora; the far left bright spot connects magnetically to Io; the spots at the bottom of the image lead to Ganymede and Europa.

The aurorae on Saturn seem, like Earth's, to be powered by the solar wind. However, Jupiter's aurorae are more complex. Jupiter's main auroral oval is associated with the plasma produced by the volcanic moon Io, and the transport of this plasma within the planet's magnetosphere. An uncertain fraction of Jupiter's aurorae are powered by the solar wind. In addition, the moons, especially Io, are also powerful sources of aurora. These arise from electric currents along field lines ("field aligned currents"), generated by a dynamo mechanism due to the relative motion between the rotating planet and the moving moon. Io, which has active volcanism and an ionosphere, is a particularly strong source, and its currents also generate radio emissions, which have been studied since 1955. Using the Hubble Space Telescope, auroras over Io, Europa and Ganymede have all been observed.

An aurora high above the northern part of Saturn; image taken by the Cassini spacecraft. A movie shows images from 81 hours of observations of Saturn's aurora.

Auroras have also been observed on Venus and Mars. Venus has no magnetic field and so Venusian auroras appear as bright and diffuse patches of varying shape and intensity, sometimes distributed over the full disc of the planet.[96] A Venusian aurora originates when electrons from the solar wind collide with the night-side atmosphere.

An aurora was detected on Mars, on 14 August 2004, by the SPICAM instrument aboard *Mars Express*. The aurora was located at Terra Cimmeria, in the region of 177° east, 52° south. The total size of the emission region was about 30 km across, and possibly about 8 km high. By analyzing a map of crustal magnetic anomalies compiled with data from Mars Global Surveyor, scientists observed that the region of the emissions corresponded to an area where the strongest magnetic field is localized. This correlation indicated that the origin of the light emission was a flux of electrons moving along the crust magnetic lines and exciting the upper atmosphere of Mars.[95][97]

Between 2014 and 2016, cometary auroras were observed on comet 67P/Churyumov–Gerasimenko by multiple instruments on the Rosetta spacecraft.[98][99] The auroras were observed at far-ultraviolet wavelengths. Coma observations revealed atomic emissions of hydrogen and oxygen caused by the photodissociation (not photoionization, like in terrestrial auroras) of water molecules in the comet's coma.[99] The interaction of accelerated electrons from the solar wind with gas particles in the coma is responsible for the aurora.[99] Since comet 67P has no magnetic field, the aurora is diffusely spread around the comet.[99]

Exoplanets, such as hot Jupiters, have been suggested to experience ionization in their upper atmospheres and generate an aurora modified by weather in their turbulent tropospheres.[100] However, there is no current detection of an exoplanet aurora.

The first ever extra-solar auroras were discovered in July 2015 over the brown dwarf star LSR J1835+3259.[101] The mainly red aurora was found to be a million times brighter than the northern lights, a result of the charged particles interacting with hydrogen in the atmosphere. It has been speculated that stellar winds may be stripping off material from the surface of the brown dwarf to produce their own electrons. Another possible explanation for the auroras is that an as-yet-undetected body around the dwarf star is throwing off material, as is the case with Jupiter and its moon Io.[102]

See also

- Airglow
- Aurora (heraldry)
- Heliophysics
- List of plasma physics articles
- List of solar storms
- Paschen's law
- Space tornado
- Space weather

Explanatory notes

a. Modern style guides recommend that the names of meteorological phenomena, such as aurora borealis, be uncapitalized.[2]
b. The name "auroras" is now the more common plural in the US; however, *aurorae* is the original Latin plural and is often used by scientists. In some contexts, aurora is an uncountable noun, multiple sightings being referred to as "the aurora".
c. The aurorae seen in northern latitudes, around the Arctic, can be referred to as the **northern lights** or **aurora borealis**, while those seen in southern latitudes, around the Antarctic, are known as the **southern lights** or **aurora australis**. **Polar lights** and **aurora polaris** are the more general equivalents of these terms.

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External links

- Aurora forecast – Will there be northern lights? (https://www.nordlysvarsel.com/)
- Current global map showing the probability of visible aurora (https://earth.nullschool.net/#current/space/surface/level/anim=off/overlay=aurora/winkel3/)
- Aurora – Forecasting (https://web.archive.org/web/20161124084503/http://www.gi.alaska.edu/AuroraForecast) (archived 24 November 2016)
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- Solar Terrestrial Data (http://www.hamqsl.com/solar1.html#converters) – Online Converter – *Northern Lights* Latitude
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- Live Northern Lights webstream (https://news.avclub.com/bask-in-natures-majesty-without-getting-your-tootsies-c-1841696490)

- World's Best Aurora (https://spectacularnwt.com/what-to-do/aurora) – The Northwest Territories is the world's Northern Lights mecca.

Multimedia

- Amazing time-lapse video of Aurora Borealis (https://vimeo.com/user10702000/fireinthesky) – Shot in Iceland over the winter of 2013/2014
- Popular video of Aurora Borealis (http://nrk.no/nyheter/distrikt/troms_og_finnmark/1.7467857) – Taken in Norway in 2011
- Aurora Photo Gallery (https://web.archive.org/web/20111004061641/http://www.aurora-northern-lights.com/) – Views taken 2009–2011 (archived 4 October 2011)
- Aurora Photo Gallery (http://apod.nasa.gov/apod/ap120103.html) – "Full-Sky Aurora" over Eastern Norway. December 2011
- Videos and Photos – Auroras at Night (https://web.archive.org/web/20100902122923/http://www.twanight.org/newTWAN/gallery.asp?Gallery=Aurora&page=1) (archived 2 September 2010)
- Video (04:49) (https://www.youtube.com/watch?v=lT3J6a9p_o8) – Aurora Borealis – How The *Northern Lights* Are Created (video on YouTube)
- Video (47:40) (http://www.nfb.ca/film/northern_lights) – *Northern Lights* – Documentary
- Video (5:00) (https://vimeo.com/62602652) – Northern lights video in real time
- Video (01:42) (https://web.archive.org/web/20110817082341/http://vimeo.com/27315234) – *Northern Light – Story of Geomagnetc Storm (Terschelling Island – 6/7 April 2000) (archived 17 August 2011)*
- Video (01:56) (https://www.youtube.com/watch?v=Lc3FxNXjBs0) (time-lapse) − Auroras – Ground-Level View from Finnish Lapland 2011 (video on YouTube)
- Video (02:43) (https://www.youtube.com/watch?v=Vq3o3sYpk78) (time-lapse) − Auroras – Ground-Level View from Tromsø, Norway, 24 November 2010 (video on YouTube)
- Video (00:27) (https://www.youtube.com/watch?v=l6ahFFFQBZY) (time-lapse) – Earth and Auroras – Viewed from the International Space Station (video on YouTube)

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Rabbit

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Rabbit

Rabbits, also known as **bunnies** or **bunny rabbits**, are small mammals in the family Leporidae (which also contains the hares) of the order Lagomorpha (which also contains the pikas). *Oryctolagus cuniculus* includes the European rabbit species and its descendants, the world's 305 breeds[1] of domestic rabbit. *Sylvilagus* includes 13 wild rabbit species, among them the seven types of cottontail. The European rabbit, which has been introduced on every continent except Antarctica, is familiar throughout the world as a wild prey animal and as a domesticated form of livestock and pet. With its widespread effect on ecologies and cultures, the rabbit is, in many areas of the world, a part of daily life – as food, clothing, a companion, and a source of artistic inspiration.

Although once considered rodents, lagomorphs like rabbits have been discovered to have diverged separately and earlier than their rodent cousins and have a number of traits rodents lack, like two extra incisors.

Rabbit

Temporal range: Late Eocene – Holocene,

European rabbit (*Oryctolagus cuniculus*)

Scientific classification	
Domain:	Eukaryota
Kingdom:	Animalia
Phylum:	Chordata
Class:	Mammalia
Order:	Lagomorpha
Family:	Leporidae

Included genera

Pentalagus
Bunolagus
Nesolagus
Romerolagus
Brachylagus
Sylvilagus
Oryctolagus

Terminology and etymology

A male rabbit is called a *buck*; a female is called a *doe*. An older term for an adult rabbit used until the 18th century is *coney* (derived ultimately from the Latin *cuniculus*), while *rabbit* once referred only to the young animals.[2] Another term for a young rabbit is *bunny*, though this term is often applied informally (particularly by children) to rabbits generally, especially domestic ones. More recently, the term *kit* or *kitten* has been used to refer to a young rabbit.

A group of rabbits is known as a *colony* or *nest* (or, occasionally, a *warren*, though this more commonly refers to where the rabbits live).[3] A group of baby rabbits produced from a single mating is referred to as a *litter*[4] and a group of domestic rabbits living together is sometimes called a *herd*.[5]

The word rabbit itself derives from the Middle English *rabet*, a borrowing from the Walloon *robète*, which was a diminutive of the French or Middle Dutch *robbe*.[6]

Taxonomy

Poelagus

Rabbits and hares were formerly classified in the order Rodentia (rodent) until 1912, when they were moved into a new order, Lagomorpha (which also includes pikas). Below are some of the genera and species of the rabbit.

Brachylagus idahoensis

Pygmy rabbit

Nesolagus netscheri

Sumatran Striped Rabbit

(Model)

Oryctolagus cuniculus

European rabbit

(Feral Tasmanian specimen)

Pentalagus furnessi

Amami rabbit

(Taxidermy specimen)

Romerolagus diazi

Volcano rabbit

(Taxidermy specimen)

Sylvilagus aquaticus

Swamp rabbit

(Juvenile)

Sylvilagus audubonii

Desert cottontail

Sylvilagus bachmani

Brush rabbit

Sylvilagus brasiliensis

Tapeti

(Taxidermy specimen)

Sylvilagus floridanus

Eastern cottontail

- Order **Lagomorpha**
  - Family **Leporidae** (in part)
- Genus *Brachylagus*
  - Pygmy rabbit, *Brachylagus idahoensis*
- Genus *Bunolagus*
  - Bushman rabbit, *Bunolagus monticularis*
- Genus *Lepus*[a]
- Genus *Nesolagus*
  - Sumatran striped rabbit, *Nesolagus netscheri*
  - Annamite striped rabbit, *Nesolagus timminsi*
- Genus *Oryctolagus*
  - European rabbit, *Oryctolagus cuniculus*
- Genus *Pentalagus*
  - Amami rabbit/Ryūkyū rabbit, *Pentalagus furnessi*
- Genus *Poelagus*
  - Central African Rabbit, *Poelagus marjorita*
- Genus *Romerolagus*
  - Volcano rabbit, *Romerolagus diazi*

- Genus *Sylvilagus*
  - Swamp rabbit, *Sylvilagus aquaticus*
  - Desert cottontail, *Sylvilagus audubonii*
  - Brush rabbit, *Sylvilagus bachmani*
  - Forest rabbit, *Sylvilagus brasiliensis*
  - Mexican cottontail, *Sylvilagus cunicularis*
  - Dice's cottontail, *Sylvilagus dicei*
  - Eastern cottontail, *Sylvilagus floridanus*
  - Tres Marias rabbit, *Sylvilagus graysoni*
  - Omilteme cottontail, *Sylvilagus insonus*
  - San Jose brush rabbit, *Sylvilagus mansuetus*
  - Mountain cottontail, *Sylvilagus nuttallii*
  - Marsh rabbit, *Sylvilagus palustris*
  - New England cottontail, *Sylvilagus transitionalis*

Differences from hares

The term *rabbit* is typically used for all Leporidae species excluding the genus *Lepus*. Members of that genus are instead known as hares or jackrabbits.

Hare

Johann Daniel Meyer (1748)

Rabbit

Johann Daniel Meyer (1748)

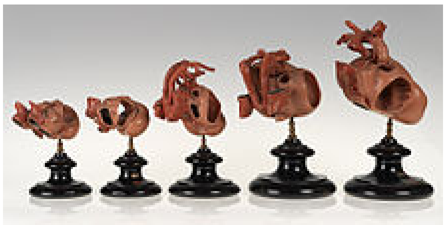
Lepus species are typically precocial, born relatively mature and mobile with hair and good vision, while rabbit species are altricial, born hairless and blind, and requiring closer care. Hares live a relatively solitary life in a simple nest above the ground, while most rabbits live in social groups in burrows or warrens. Hares are generally larger than rabbits, with ears that are more elongated, and with hind legs that are larger and longer. Descendants of the European rabbit are commonly bred as livestock and kept as pets, whereas no hares have been domesticated – the breed called the Belgian hare is actually a domestic rabbit which has been selectively bred to resemble a hare.

Domestication

Rabbits have long been domesticated. Beginning in the Middle Ages, the European rabbit has been widely kept as livestock, starting in ancient Rome. Selective breeding has generated a wide variety of rabbit breeds, of which many (since the early 19th century) are also kept as pets. Some strains of rabbit have been bred specifically as research subjects.

As livestock, rabbits are bred for their meat and fur. The earliest breeds were important sources of meat, and so became larger than wild rabbits, but domestic rabbits in modern times range in size from dwarf to giant. Rabbit fur, prized for its softness, can be found in a broad range of coat colors and patterns, as well as lengths. The Angora rabbit breed, for example, was developed for its long, silky fur, which is often hand-spun into yarn. Other domestic rabbit breeds have been developed primarily for the commercial fur trade, including the Rex, which has a short plush coat.

Biology



Wax models showing the development of the rabbit heart

Evolution

Because the rabbit's epiglottis is engaged over the soft palate except when swallowing, the rabbit is an obligate nasal breather. Rabbits have two sets of incisor teeth, one behind the other. This way they can be distinguished from rodents, with which they are often confused.[7] Carl Linnaeus originally grouped rabbits and rodents under the class Glires; later, they were separated as the scientific consensus is that many of their similarities were a result of convergent evolution. Recent DNA analysis and the discovery of a common ancestor has supported the view that they share a common lineage, so rabbits and rodents are now often grouped together in the superorder Glires.[8]

Morphology

Skeleton of the rabbit

Since speed and agility are a rabbit's main defenses against predators (including the swift fox), rabbits have large hind leg bones and well-developed musculature. Though plantigrade at rest, rabbits are on their toes while running, assuming a more digitigrade posture. Rabbits use their strong claws for digging and (along with their teeth) for defense.[9] Each front foot has four toes plus a dewclaw. Each hind foot has four toes (but no dewclaw).[10]

Most wild rabbits (especially compared to hares) have relatively full, egg-shaped bodies. The soft coat of the wild rabbit is agouti in coloration (or, rarely, melanistic), which aids in camouflage. The tail of the rabbit (with the exception of the cottontail species) is dark on top and white below. Cottontails have white on the top of their tails.[11]

As a result of the position of the eyes in its skull, the rabbit has a field of vision that encompasses nearly 360 degrees, with just a small blind spot at the bridge of the nose.[12]

Hind limb elements

The anatomy of rabbits' hind limbs is structurally similar to that of other land mammals and contributes to their specialized form of locomotion. The bones of the hind limbs consist of long bones (the femur, tibia, fibula, and phalanges) as well as short bones (the tarsals). These bones are created through endochondral ossification during development. Like most land mammals, the round head of the femur articulates with the

This image comes from a specimen in the Pacific Lutheran University natural history collection. It displays all of the skeletal articulations of rabbit's hind limbs.

Melanistic coloring

Oryctologus cuniculus

European rabbit (wild)

acetabulum of the os coxae. The femur articulates with the tibia, but not the fibula, which is fused to the tibia. The tibia and fibula articulate with the tarsals of the pes, commonly called the foot. The hind limbs of the rabbit are longer than the front limbs. This allows them to produce their hopping form of locomotion. Longer hind limbs are more capable of producing faster speeds. Hares, which have longer legs than cottontail rabbits, are able to move considerably faster.[13] Rabbits stay just on their toes when moving; this is called digitigrade locomotion. The hind feet have four long toes that allow for this and are webbed to prevent them from spreading when hopping.[14] Rabbits do not have paw pads on their feet like most other animals that use digitigrade locomotion. Instead, they have coarse compressed hair that offers protection.[15]

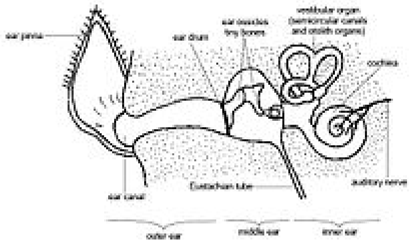
Musculature

The rabbit's hind limb (lateral view) includes muscles involved in the quadriceps and hamstrings.

Rabbits have muscled hind legs that allow for maximum force, maneuverability, and acceleration that is divided into three main parts: foot, thigh, and leg. The hind limbs of a rabbit are an exaggerated feature. They are much longer than the forelimbs, providing more force. Rabbits run on their toes to gain the optimal stride during locomotion. The force put out by the hind limbs is contributed by both the structural anatomy of the fusion tibia and fibula, and muscular features.[16] Bone formation and removal, from a cellular standpoint, is directly correlated to hind limb muscles. Action pressure from muscles creates force that is then distributed through the skeletal structures. Rabbits that generate less force, putting less stress on bones are more prone to osteoporosis due to bone rarefaction.[17] In rabbits, the more fibers in a muscle, the more resistant to fatigue. For example, hares have a greater resistance to fatigue than cottontails. The muscles of rabbit's hind limbs can be classified into four main categories: hamstrings, quadriceps, dorsiflexors, or plantar flexors. The quadriceps muscles are in charge of force production when jumping. Complementing these muscles are the hamstrings, which aid in short bursts of action. These muscles play off of one another in the same way as the plantar flexors and dorsiflexors, contributing to the generation and actions associated with force.[18]

Ears

Within the order lagomorphs, the ears are used to detect and avoid predators. In the family Leporidae, the ears are typically longer than they are wide. For example, in black tailed jack rabbits, their long ears cover a greater surface area relative to their body size that allow them to detect predators from far away. In contrast with cottontail rabbits, their ears are smaller and shorter, requiring that predators be closer before they can detect them and flee. Evolution has favored rabbits having shorter ears, so the larger surface area does not cause them to lose heat in more temperate regions. The opposite can be seen in rabbits that live in hotter climates; possessing longer ears with a larger surface area helps with dispersion of heat. Since sound travels less well in arid as opposed to cooler air, longer ears may aid the organism in detecting predators sooner rather than later, in warmer temperatures.[19] Rabbits are characterized by shorter ears than hares.[20] Rabbits' ears are an important structure to aid thermoregulation as well as in detecting predators due to the way the outer, middle, and inner ear muscles coordinate with one another. The ear muscles also aid in maintaining balance and movement when fleeing predators.[21]



Anatomy of mammalian ear

Outer ear

The auricle, also known as the pinna, is a rabbit's outer ear.[22] The rabbit's pinnae represent a fair part of the body surface area. It is theorized that the ears aid in dispersion of heat at temperatures above 30 °C with rabbits in warmer climates having longer pinnae due to this. Another theory is that the ears function as shock absorbers that could aid and stabilize rabbits' vision when fleeing predators, but this has typically only been seen in hares.[23] The rest of the outer ear has bent canals that lead to the eardrum or tympanic membrane.[24]


A Holland Lop resting with one ear up and one ear down. Some rabbits can adjust their ears to hear distant sounds.

Middle ear

The middle ear, separated by the outer eardrum in the back of the rabbit's skull, contains three bones: the hammer, anvil, and stirrup, collectively called ossicles, which act to decrease sound before it hits the inner ear; in general, the ossicles act as a barrier to the inner ear for sound energy.[24]

Inner ear

Inner ear fluid, called endolymph, receives the sound energy. After receiving the energy. The inner ear comprises two parts: the cochlea that uses sound waves from the ossicles, and the vestibular apparatus that manages the rabbit's position in regard to movement. Within the cochlea a basilar membrane contains sensory hair structures that send nerve signals to the brain, allowing it to recognize different sound frequencies. Within the vestibular apparatus three semicircular canals help detect angular motion.[24]

Dewlaps

A dewlap is a secondary sex characteristic in rabbits, caused by the presence of female sex hormones. They develop with puberty. A female rabbit who has been neutered before reaching sexual maturity will not develop a dewlap, and even if a doe is neutered after developing a dewlap, the dewlap will gradually disappear over several months. This also aligns with the results of injecting male rabbits with female sex hormones, specifically the ones from pregnant women's urine. The male rabbits developed dewlaps, which then gradually disappeared once administration had ceased.[25] (This is not the process of the rabbit test, a common way to test for human female pregnancy in the 20th century; the pregnancy test involve dissecting female rabbits after injection with urine to see if their ovaries had enlarged.)[26] While it is unclear exactly what function a dewlap performs, pregnant female rabbits will pluck fur from their dewlaps shortly before giving birth to line a nest for their young.[27]

Thermoregulation

Rabbits use their large, vascularized ears, which aid in thermoregulation, to keep their body temperature at an optimal level.

Thermoregulation is the process that an organism uses to maintain an optimal body temperature independent of external conditions.[28] This process is carried out by the pinnae, which takes up most of the rabbit's body surface and contain a vascular network and arteriovenous shunts.[29] In a rabbit, the optimal body temperature is around 38.5–40 °C.[30] If their body temperature exceeds or does not meet this optimal temperature, the rabbit must return to homeostasis. Homeostasis of body temperature is maintained by the use of their large, highly vascularized ears that are able to change the amount of blood flow that passes through the ears.

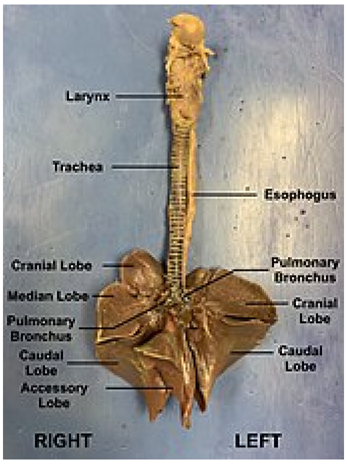
Constriction and dilation of blood vessels in the ears are used to control the core body temperature of a rabbit. If the core temperature exceeds its optimal temperature greatly, blood flow is constricted to limit the amount of blood going through the vessels. With this constriction, there is only a limited amount of blood that is passing through the ears where ambient heat would be able to heat the blood that is flowing through the ears and therefore, increasing the body temperature. Constriction is also used when the ambient temperature is much lower than that of the rabbit's core body temperature. When the ears are constricted it again limits blood flow through the ears to conserve the optimal body temperature of the rabbit. If the ambient temperature is either 15 degrees above or below the optimal body temperature, the blood vessels will dilate. With the blood vessels being enlarged, the blood is able to pass through the large surface area, causing it to either heat or cool down.

During hot summers, the rabbit has the capability to stretch its pinnae, which allows for greater surface area and increase heat dissipation. In cold winters, the rabbit does the opposite and folds its ears to decrease its surface area to the ambient air, which would decrease their body temperature.

The jackrabbit has the largest ears within the *Oryctolagus cuniculus* group. Their ears contribute to 17% of their total body surface area. Their large pinna were evolved to maintain homeostasis while in the extreme temperatures of the desert.

Respiratory system

The rabbit's nasal cavity lies dorsal to the oral cavity, and the two compartments are separated by the hard and soft palate.[31] The nasal cavity itself is separated into a left and right side by a cartilage barrier, and it is covered in fine hairs that trap dust before it can enter the respiratory tract.[31][32] As the rabbit breathes, air flows in through the nostrils along the alar folds. From there, the air moves into the nasal cavity, also known as the nasopharynx, down through the trachea, through the larynx, and into the lungs.[32][33] The larynx functions as the rabbit's voice box, which enables it to produce a wide variety of sounds.[32] The trachea is a long tube embedded with cartilaginous rings that prevent the tube from collapsing as air moves in and out of the lungs. The trachea then splits into a left and right bronchus, which meet the lungs at a structure called the hilum. From there, the bronchi split into progressively more narrow and numerous branches. The bronchi branch into bronchioles, into respiratory bronchioles, and ultimately terminate at the alveolar ducts. The branching that is typically found in rabbit lungs is a clear example of monopodial branching, in which smaller branches divide out laterally from a larger central branch.[34]



Ventral view of dissected rabbit lungs with key structures labeled.

The structure of the rabbit's nasal and oral cavities necessitates breathing through the nose. This is due to the fact that the epiglottis is fixed to the backmost portion of the soft palate.[33] Within the oral cavity, a layer of tissue sits over the opening of the glottis, which blocks airflow from the oral cavity to the trachea.[31] The epiglottis functions to prevent the rabbit from aspirating on its food. Further, the presence of a soft and hard palate allow the rabbit to breathe through its nose while it feeds.[32]

Rabbits' lungs are divided into four lobes: the cranial, middle, caudal, and accessory lobes. The right lung is made up of all four lobes, while the left lung only has two: the cranial and caudal lobes.[34] To provide space for the heart, the left cranial lobe of the lungs is significantly smaller than that of the right.[31] The diaphragm is a muscular structure that lies caudal to the lungs and contracts to facilitate respiration.[31][33]


Monopodial branching as seen in dissected rabbit lungs.

Digestion

Rabbits are herbivores that feed by grazing on grass and other leafy plants. Consequently, their diet contains large amounts of cellulose, which is hard to digest. Rabbits solve this problem via a form of hindgut fermentation. They pass two distinct types of feces: hard droppings and soft black viscous pellets, the latter of which are known as caecotrophs or "night droppings"[35] and are immediately eaten (a behaviour known as *coprophagy*). Rabbits reingest their own droppings (rather than chewing the cud as do cows and numerous other herbivores) to digest their food further and extract sufficient nutrients.[36]

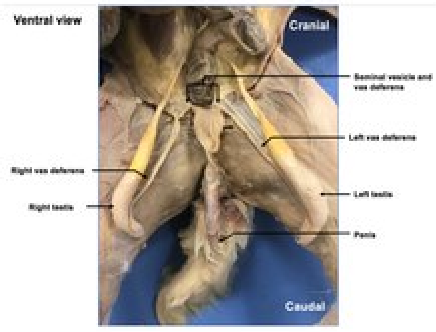
Rabbits graze heavily and rapidly for roughly the first half-hour of a grazing period (usually in the late afternoon), followed by about half an hour of more selective feeding. In this time, the rabbit will also excrete many hard fecal pellets, being waste pellets that will not be reingested. If the environment is relatively non-threatening, the rabbit will remain outdoors for many hours, grazing at intervals. While out of the burrow, the rabbit will occasionally reingest its soft, partially digested pellets; this is rarely observed, since the pellets are reingested as they are produced.

Hard pellets are made up of hay-like fragments of plant cuticle and stalk, being the final waste product after redigestion of soft pellets. These are only released outside the burrow and are not reingested. Soft pellets are usually produced several hours after grazing, after the hard pellets have all been excreted. They are made up of micro-organisms and undigested plant cell walls.

Rabbits are hindgut digesters. This means that most of their digestion takes place in their large intestine and cecum. In rabbits, the cecum is about 10 times bigger than the stomach and it along with the large intestine makes up roughly 40% of the rabbit's digestive tract.[37] The unique musculature of the cecum allows the intestinal tract of the rabbit to separate fibrous material from more digestible material; the fibrous material is passed as feces, while the more nutritious material is encased in a mucous lining as a cecotrope. Cecotropes, sometimes called "night feces", are high in minerals, vitamins and proteins that are necessary to the rabbit's health. Rabbits eat these to meet their nutritional requirements; the mucous coating allows the nutrients to pass through the acidic stomach for digestion in the intestines. This process allows rabbits to extract the necessary nutrients from their food.[38]

The chewed plant material collects in the large cecum, a secondary chamber between the large and small intestine containing large quantities of symbiotic bacteria that help with the digestion of cellulose and also produce certain B vitamins. The pellets are about 56% bacteria by dry weight, largely accounting for the pellets being 24.4% protein on average. The soft feces form here and contain up to five times the vitamins of hard feces. After being excreted, they are eaten whole by the rabbit and redigested in a special part of the stomach. The pellets remain intact for up to six hours in the stomach; the bacteria within continue to digest the plant carbohydrates. This double-digestion process enables rabbits to use nutrients that they may have missed during the first passage through the gut, as well as the nutrients formed by the microbial activity and thus ensures that maximum nutrition is derived from the food they eat.[11] This process serves the same purpose in the rabbit as rumination does in cattle and sheep.[39]

Because rabbits cannot vomit,[40] if buildup occurs within the intestines (due often to a diet with insufficient fibre),[41] intestinal blockage can occur.[42]



Dissected image of the male rabbit reproductive system with key structures labeled

Reproduction

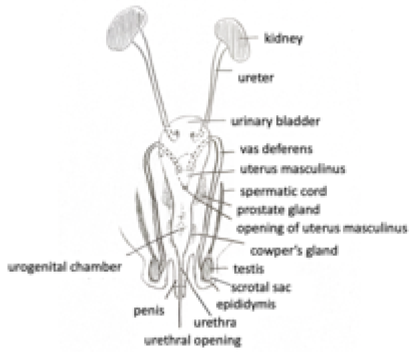


Diagram of the male rabbit reproductive system with main components labeled

The adult male reproductive system forms the same as most mammals with the seminiferous tubular compartment containing the Sertoli cells and an adluminal compartment that contains the Leydig cells.[43] The Leydig cells produce testosterone, which maintains libido[43] and creates secondary sex characteristics such as the genital tubercle and penis. The Sertoli cells triggers the production of Anti-Müllerian duct hormone, which absorbs the Müllerian duct. In an adult male rabbit, the sheath of the penis is cylinder-like and can be extruded as early as two months of age.[44] The scrotal sacs lay lateral to the penis and contain epididymal fat pads which protect the testes. Between 10 and 14 weeks, the testes descend and are able to retract into the pelvic cavity to thermoregulate.[44] Furthermore, the secondary sex characteristics, such as the testes, are complex and secrete many compounds. These compounds include fructose, citric acid, minerals, and a uniquely high amount of catalase.[43]

The adult female reproductive tract is bipartite, which prevents an embryo from translocating between uteri.[45] The two uterine horns communicate to two cervixes and forms one vaginal canal. Along with being bipartite, the female rabbit does not go through an estrus cycle, which causes mating induced ovulation.[44]

The average female rabbit becomes sexually mature at three to eight months of age and can conceive at any time of the year for the duration of her life. Egg and sperm production can begin to decline after three years.[43] During mating, the male rabbit will mount the female rabbit from behind and insert his penis into the female and make rapid pelvic hip thrusts. The encounter lasts only 20–40 seconds and after, the male will throw himself backwards off the female.[46]

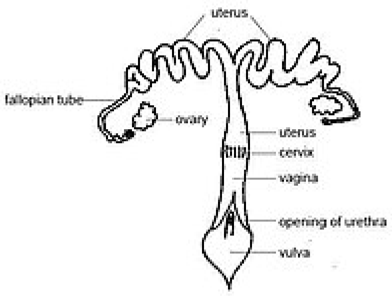


Diagram of the female rabbit reproductive system with main components labeled.

The rabbit gestation period is short and ranges from 28 to 36 days with an average period of 31 days. A longer gestation period will generally yield a smaller litter while shorter gestation periods will give birth to a larger litter. The size of a single litter can range from four to 12 kits allowing a female to deliver up to 60 new kits a year. After birth, the female can become pregnant again as early as the next day.[44]

After mating, hormonal changes will cause the doe to begin to dig a burrow for her nest about a week before giving birth. Between three days and a few hours before giving birth another series of hormonal changes will cause her to prepare the nest structure. The doe will first gather grass for a structure, and an elevation in prolactin shortly before birth will cause her fur to shed that the doe will then use to line the nest, providing insulation for the newborn kits.[47]

The mortality rates of embryos are high in rabbits and can be due to infection, trauma, poor nutrition and environmental stress so a high fertility rate is necessary to counter this.[44]

Sleep

Rabbits may appear to be crepuscular, but their natural inclination is toward nocturnal activity.[48] In 2011, the average sleep time of a rabbit in captivity was calculated at 8.4 hours per day.[49] As with other prey animals, rabbits often sleep with their eyes open, so that sudden movements will awaken the rabbit to respond to potential danger.[50]

Diseases and immunity

In addition to being at risk of disease from common pathogens such as *Bordetella bronchiseptica* and *Escherichia coli*, rabbits can contract the virulent, species-specific viruses RHD ("rabbit hemorrhagic disease", a form of calicivirus)[51] or myxomatosis. Among the parasites that infect rabbits are tapeworms (such as *Taenia serialis)*, external parasites (including fleas and mites), coccidia species, and *Toxoplasma gondii*.[52][53] Domesticated rabbits with a diet lacking in high fiber sources, such as hay and grass, are susceptible to potentially lethal gastrointestinal stasis.[54] Rabbits and hares are almost never found to be infected with rabies and have not been known to transmit rabies to humans.[55]

Encephalitozoon cuniculi, an obligate intracellular parasite is also capable of infecting many mammals including rabbits.

Rabbit immunity has significantly diverged from other tetrapods in the manner it employs immunoglobulin light chains.[56][57] In one case McCartney-Francis *et al.*, 1984 discover a unique additional disulfide bond between Cys 80 in Vκ and Cys 171 in Cκ.[56][57] They suggest that this may serve to stabilise rabbit antibodies.[56][57] Meanwhile *IGKC1* shows high amino acid divergence between domesticated types and ferals derived from them.[57] This can be as high as 40%.[57]

Rabbit hemorrhagic disease is caused by strains of rabbit hemorrhagic disease virus (RHDV) including type 2 (RHDV2).[58] RHDV2 was detected for the first time in Washington state, US in May 2022 and then in August once in Washington and twice in Oregon.[59]

Ecology

Rabbits are prey animals and are therefore constantly aware of their surroundings. For instance, in Mediterranean Europe, rabbits are the main prey of red foxes, badgers, and Iberian lynxes.[60] If confronted by a potential threat, a rabbit may freeze and observe then warn others in the warren with powerful thumps on the ground. Rabbits have a remarkably wide field of vision, and a good deal of it is devoted to overhead scanning.[61] The doe (mother) is aware that she gives off scent which can attract predators, so she will stay away from the nest to avoid putting the kits (babies) in danger, returning the nest only a few times a day to feed the kits.[62]

Rabbit kits one hour after birth

Rabbits survive predation by burrowing, hopping away in a zig-zag motion, and, if captured, delivering powerful kicks with their hind legs. Their strong teeth allow them to eat and to bite to escape a struggle.[63] The longest-lived rabbit on record, a domesticated European rabbit living in Tasmania, died at age 18.[64] The lifespan of wild rabbits is much shorter; the average longevity of an eastern cottontail, for instance, is less than one year.[65]

Habitat and range

Rabbit habitats include meadows, woods, forests, grasslands, deserts and wetlands.[66] Rabbits live in groups, and the best known species, the European rabbit, lives in burrows, or rabbit holes. A group of burrows is called a *warren*.[66]

Domestic rabbit photographed at Alligator Bay, Beauvoir, France.

More than half the world's rabbit population resides in North America.[66] They are also native to southwestern Europe, Southeast Asia, Sumatra, some islands of Japan, and in parts of Africa and South America. They are not naturally found in most of Eurasia, where a number of species of hares are present. Rabbits first entered South America relatively recently, as part of the Great American Interchange. Much of the continent has just one species of rabbit, the tapeti, while most of South America's Southern Cone is without rabbits.

The European rabbit has been introduced to many places around the world.[11] A recent study found that "the (so-called) Chinese rabbits were introduced from Europe. Genetic diversity in Chinese rabbits was very low."[67]

Rabbits have been launched into space orbit.[68]

Environmental problems

Impact of rabbit-proof fence, Cobar, New South Wales, 1905

Rabbits have been a source of environmental problems when introduced into the wild by humans. As a result of their appetites, and the rate at which they breed, feral rabbit depredation can be problematic for agriculture. Gassing (fumigation of warrens),[69] barriers (fences), shooting, snaring, and ferreting have been used to control rabbit populations, but the most effective measures are diseases such as myxomatosis (*myxo* or *mixi*, colloquially) and calicivirus. In Europe, where rabbits are farmed on a large scale, they are protected against myxomatosis and calicivirus with a genetically modified virus. The virus was developed in Spain, and is beneficial to rabbit farmers. If it were to make its way into wild populations in areas such as Australia, it could create a population boom, as those diseases are the most serious threats to rabbit survival. Rabbits in Australia and New Zealand are considered to be such a pest that land owners are legally obliged to control them.[70][71]

Rabbits are known to be able to catch fire and spread wildfires, but the efficiency and relevance of this method has been doubted by forest experts who contend that a rabbit on fire could move some meters.[72][73] Knowledge on fire-spreading rabbits is based on anecdotes as there is no known scientific investigation on the subject.[73]

As food and clothing

In some areas, wild rabbits and hares are hunted for their meat, a lean source of high quality protein.[74] In the wild, such hunting is accomplished with the aid of trained falcons, ferrets, or dogs, as well as with snares or other traps, and rifles. A caught rabbit may be dispatched with a sharp blow to the back of its head, a practice from which the term *rabbit punch* is derived.

Wild leporids comprise a small portion of global rabbit-meat consumption. Domesticated descendants of the European rabbit *(Oryctolagus cuniculus)* that are bred and kept as livestock (a practice called cuniculture) account for the estimated 200 million tons of rabbit meat produced annually.[75] Approximately 1.2 billion rabbits are slaughtered each year for meat worldwide.[76] In 1994, the countries with the highest consumption per capita of rabbit meat were Malta with 8.89 kg (19 lb 10 oz), Italy with 5.71 kg (12 lb 9 oz), and Cyprus with 4.37 kg (9 lb 10 oz), falling to 0.03 kg (1 oz) in Japan. The figure for the United States was 0.14 kg (5 oz) per capita. The largest producers of rabbit meat in 1994 were China, Russia, Italy, France, and Spain.[77] Rabbit meat was once a common commodity in Sydney, but declined after the myxomatosis virus was intentionally introduced to control the exploding population of feral rabbits in the area.

In the United Kingdom, fresh rabbit is sold in butcher shops and markets, and some supermarkets sell frozen rabbit meat. At farmers markets there, including the famous Borough Market in London, rabbit carcasses are sometimes displayed hanging, unbutchered (in the traditional style), next to braces of pheasant or other small game. Rabbit meat is a feature of Moroccan cuisine, where it is cooked in a tajine with "raisins and grilled almonds added a few minutes before serving".[78] In China, rabbit meat is particularly popular in Sichuan cuisine, with its stewed rabbit, spicy diced rabbit, BBQ-style rabbit, and even spicy rabbit heads, which have been compared to *spicy duck neck*.[75] Rabbit meat is comparatively unpopular elsewhere in the Asia-Pacific.

An extremely rare infection associated with rabbits-as-food is tularemia (also known as *rabbit fever*), which may be contracted from an infected rabbit.[79] Hunters are at higher risk for tularemia because of the potential for inhaling the bacteria during the skinning process.

In addition to their meat, rabbits are used for their wool, fur, and pelts, as well as their nitrogen-rich manure and their high-protein milk.[80] Production industries have developed domesticated rabbit breeds (such as the well-known Angora rabbit) to efficiently fill these needs.

Behaviors

"Binkies" in rabbits is characterized by a sudden kicks with their hind legs, shaking their head sideways (usually mid-air), and running around rapidly; usually called "zooming". There's also "half binky", which is characterized by a shorter span sharp flick of its head, both types of "binkies" indicate happiness or excitement. All of which typically only lasting for around a second. A rabbit might do quick rapid multiple "binkies" in one session. It's thought to be a practice run in case they need to escape from danger.[81] Such behavior commonly occurs in domesticated rabbits living in a comfortable environment, e.g. in home.[82]

Rabbits mostly use full-body actions, like "flopping" to communicate 'emotion' to other rabbits and humans. Rabbit displaying "flopping" in front of other rabbits can be meant as a non-aggressive insult.[83][84] Rabbits commonly smell the ground first and then tilt their head to the side with a subtle jerky movement in order to lie down to its side. Which occur together with a "dramatic" instant "flopping", exposing their belly.

They may thump their hind feet on the ground to signal other rabbits that they're feeling threatened or that potential dangers are near their territory. Some domesticated rabbits might thump to get their owner's attention. Not all rabbits thump.[85]

Both sexes of rabbits often rub their chin to objects or people with their scent gland located under the chin. This is the rabbit’s way of marking their territory or possessions for the other rabbits to know by depositing scent gland secretions,[86] similar to that of cats and dogs. Rabbits who have bonded will respect each others' smell that indicates territorial border.[87]

In art, literature, and culture

Rabbits are often used as a symbol of fertility or rebirth, and have long been associated with spring and Easter as the Easter Bunny. The species' role as a prey animal with few defenses evokes vulnerability and innocence, and in folklore and modern children's stories, rabbits often appear as sympathetic characters, able to connect easily with youth of all kinds (for example, the Velveteen Rabbit, or Thumper in *Bambi*).

With its reputation as a prolific breeder, the rabbit juxtaposes sexuality with innocence, as in the Playboy Bunny. The rabbit (as a swift prey animal) is also known for its speed, agility, and endurance, symbolized (for example) by the marketing icons the Energizer Bunny and the Duracell Bunny.

Folklore

The rabbit often appears in folklore as the trickster archetype, as he uses his cunning to outwit his enemies.

- In Aztec mythology, a pantheon of four hundred rabbit gods known as Centzon Totochtin, led by Ometochtli or Two Rabbit, represented fertility, parties, and drunkenness.

- In Central Africa, the common hare (*Kalulu*), is "inevitably described" as a trickster figure.[88]
- In Chinese folklore, rabbits accompany Chang'e on the Moon. In the Chinese New Year, the zodiacal rabbit is one of the twelve celestial animals in the Chinese zodiac. Note that the Vietnamese zodiac includes a zodiacal cat in place of the rabbit, possibly because rabbits did not inhabit Vietnam. The most common explanation is that the ancient Vietnamese word for "rabbit" *(mao)* sounds like the Chinese word for "cat" (卯, *mao)*.[89]
- In Japanese tradition, rabbits live on the Moon where they make mochi, the popular snack of mashed sticky rice. This comes from interpreting the pattern of dark patches on the moon as a rabbit standing on tiptoes on the left pounding on an usu, a Japanese mortar.
- In Jewish folklore, rabbits (shfanim שפנים) are associated with cowardice, a usage still current in contemporary Israeli spoken Hebrew (similar to the English colloquial use of "chicken" to denote cowardice).
- In Korean mythology, as in Japanese, rabbits live on the moon making rice cakes ("Tteok" in Korean).
- In Anishinaabe traditional beliefs, held by the Ojibwe and some other Native American peoples, Nanabozho, or Great Rabbit, is an important deity related to the creation of the world.
- A Vietnamese mythological story portrays the rabbit of innocence and youthfulness. The gods of the myth are shown to be hunting and killing rabbits to show off their power.
- Buddhism, Christianity, and Judaism have associations with an ancient circular motif called the *three rabbits* (or "three hares"). Its meaning ranges from "peace and tranquility", to purity or the Holy Trinity, to Kabbalistic levels of the soul or to the Jewish diaspora. The tripartite symbol also appears in heraldry and even tattoos.

The rabbit as trickster is a part of American popular culture, as Br'er Rabbit (from African-American folktales and, later, Disney animation) and Bugs Bunny (the cartoon character from Warner Bros.), for example.

Anthropomorphized rabbits have appeared in film and literature, in *Alice's Adventures in Wonderland* (the White Rabbit and the March Hare characters), in *Watership Down* (including the film and television adaptations), in *Rabbit Hill* (by Robert Lawson), and in the *Peter Rabbit* stories (by Beatrix Potter). In the 1920s *Oswald the Lucky Rabbit* was a popular cartoon character.

A rabbit's foot may be carried as an amulet, believed to bring protection and good luck. This belief is found in many parts of the world, with the earliest use being recorded in Europe c. 600 BC.[90]

On the Isle of Portland in Dorset, UK, the rabbit is said to be unlucky and even speaking the creature's name can cause upset among older island residents. This is thought to date back to early times in the local quarrying industry where (to save space) extracted stones that were not fit for sale were set aside in what became tall, unstable walls. The local rabbits' tendency to burrow there would weaken the walls and their collapse resulted in injuries or even death. Thus, invoking the name of the culprit became an unlucky act to be avoided. In the local culture to this day, the rabbit (when he has to be referred to) may instead be called a "long ears" or "underground mutton", so as not to risk bringing a downfall upon oneself.[91]

In other parts of Britain and in North America, invoking the rabbit's name may instead bring good luck. "Rabbit rabbit rabbit" is one variant of an apotropaic or talismanic superstition that involves saying or repeating the word "rabbit" (or "rabbits" or "white rabbits" or some combination thereof) out loud upon waking on the first day of each month, because doing so will ensure good fortune for the duration of that month.[92]

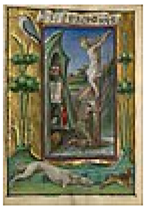
The "rabbit test" is a term, first used in 1949, for the Friedman test, an early diagnostic tool for detecting a pregnancy in humans. It is a common misconception (or perhaps an urban legend) that the test-rabbit would die if the woman was pregnant. This led to the phrase "the rabbit died" becoming a euphemism for a positive pregnancy test.[93]

Rabbit fools Elephant by showing the reflection of the moon. Illustration (from 1354) of the *Panchatantra*

"Three rabbits" motif, Coat of arms of Corbenay, France

Beatrix Potter's Peter Rabbit

WWII USAF pilot D. R. Emerson "with a rabbit's foot talisman, a gift from a New York girl friend"



Saint Jerome in the Desert, by Taddeo Crivelli (died about 1479)
[Note rabbit being chased by a domesticated hound]

See also

Lagomorpha portal

- Animal track
- Cuniculture
- Dwarf rabbit
- Hare games
- Jackalope
- Lethal dwarfism in rabbits

- List of animal names
- List of rabbit breeds
- Lop rabbit
- Rabbits in the arts
- Rabbit show jumping

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Notes

a. This genus is considered a hare, not a rabbit

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External links

- American Rabbit Breeders Association (http://www.arba.net/) organization, which promotes all phases of rabbit keeping
- House Rabbit Society (https://www.rabbit.org/) an activist organization that promotes keeping rabbits indoors

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