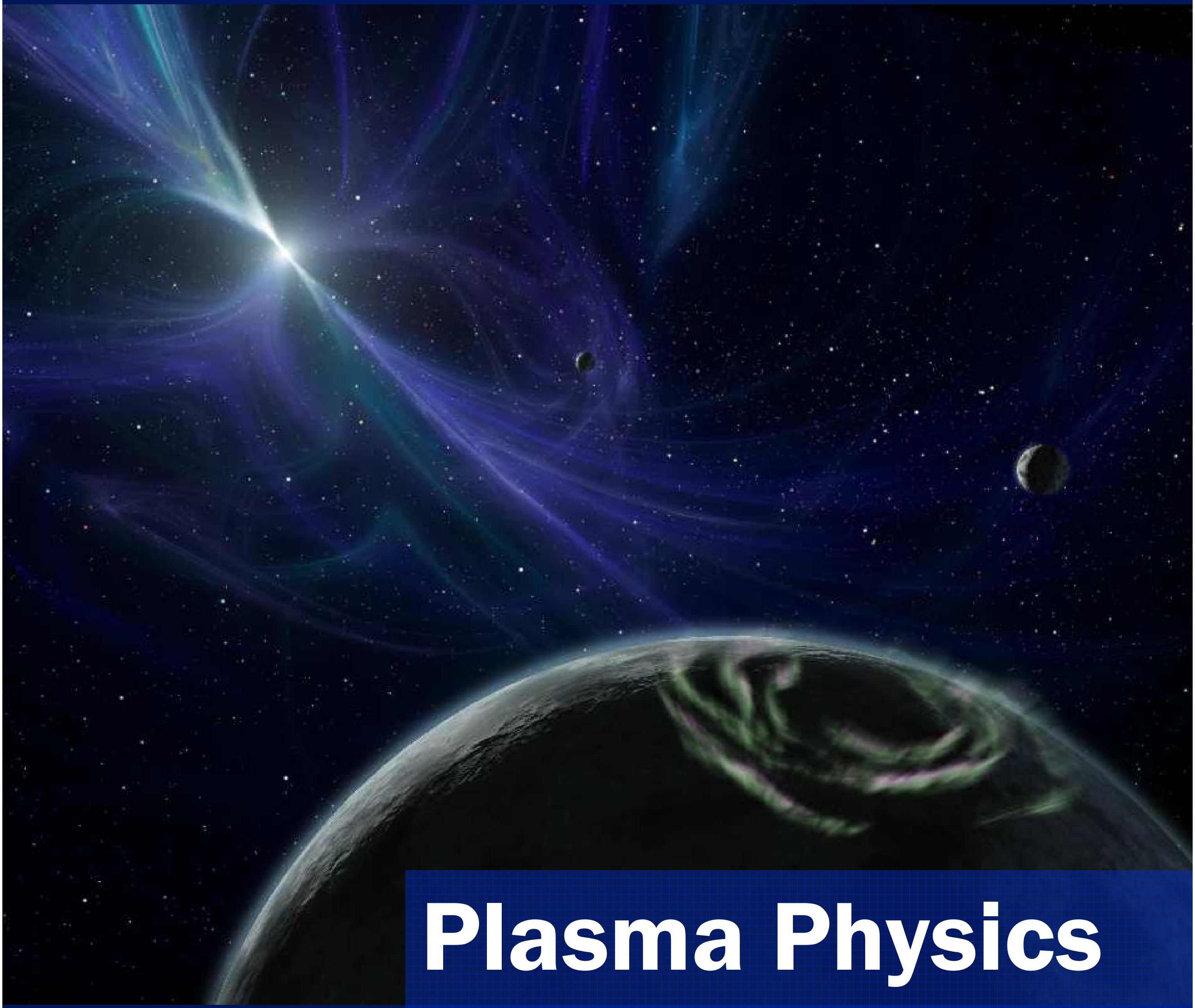

Plasma Physics and Pulsars

On the evolution of compact objects and plasma physics in weak and strong gravitational and electromagnetic fields

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as part of an internship at the Max Planck Institute for Radioastronomy, Bonn

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This composition was written as part of two internships at the Max Planck Institute for Radioastronomy in April 2009 at the Radiotelescope in Effelsberg and in February/March 2010 at the Institute in Bonn. I am very grateful for the support, expertise and patience of Axel Jessner, Maria Massi and Li Kejia, who supervised my internship and introduced me to the basic concepts and the current research in the field.

Contents

I. The life-cycle of stars

1. Formation and inner structure

Stars are formed in molecular clouds in the interstellar medium, which consist mostly of molecular hydrogen (primordial elements made a few minutes after the beginning of the universe) and dust. The dust originates from the cool surfaces of supergiants, massive stars in a late stage of stellar evolution. The clouds can range in size from less than a light year to several hundred light years across and range in mass from 10 to 10 million solar masses. They form complex shapes with filaments and clumps, and while most parts are cold at about 10K, some parts can reach up to 2000K. Dust shields the cloud interiors from ultraviolet starlight, which enables their centers to cool. To form a protostar, a compression of the order 10^{20} is needed – this happens when regions of higher density collapse as their internal gas pressure can no longer withstand gravitational forces. The cooler parts are more likely to collapse, as their thermal pressure is lower. It is likely that star formation is triggered by sudden perturbations like the passage of a shock wave or a shell of expanding gas from a supernova remnant, which induce an instability in a critical mass of the cloud.

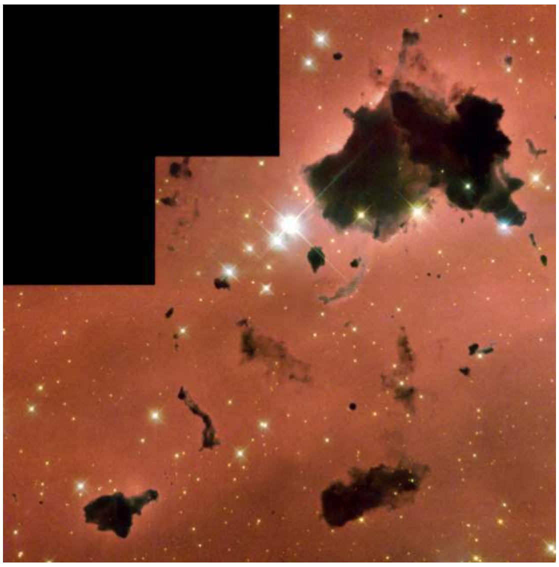
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FIG 1. 1 This cloud of dark dust is a Bok globule, a region where star formation might take place.

Once the pressure gradient within the star is exactly balanced by the force of gravity, a hydrostatic equilibrium is reached and the star becomes stable.

Stars more massive than several solar masses are observed to form in small groups in the densest regions of the clouds. About half of all stars are in binaries.

Due to the conversion of gravitational pressure into heat, the highest temperatures in every star are reached in the core. In this zone nuclear fusion processes take place, unless the star's mass is below 0.1 solar masses (2×10^{19} kg), and therefore never reaches the necessary temperature of at least 4×10^{6} K, enabling nuclear fusion. These sub-stellar objects are called "brown dwarfs", and concerning their mass they fall between gas giants (like Jupiter) and small stars.

Stars with a sufficient mass to reach temperatures to enable nuclear fusion develop a distinct inner structure of zones, whose nature and quantity is entirely determined by the mass of the star.

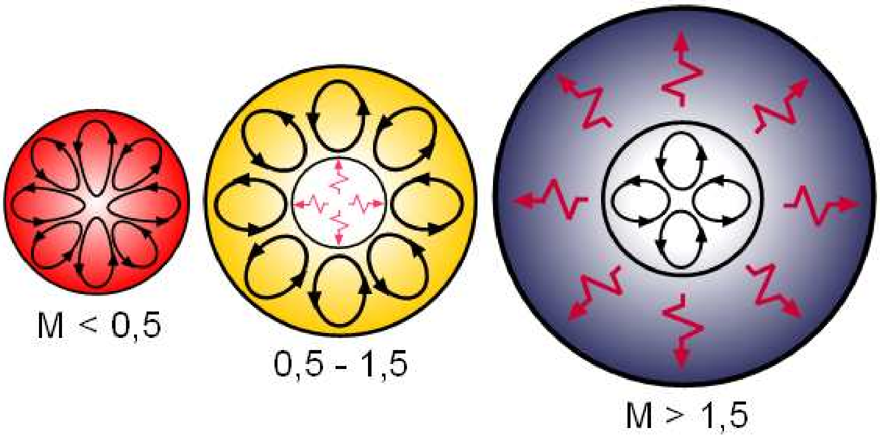

FIG 1. 2 Inner structure of stars with varying mass.

Small stars with a mass below 0.4 solar masses consist of a nuclear fusion zone at their core and a surrounding cooler zone. In this so-called 'convective zone' circular plasma currents exchange hotter plasma from within with the outer, cooler plasma, resulting in a circular flow of plasma ('convection'). The motion of this conductive plasma is believed to act like a dynamo and thus creates the magnetic field of the star.

With an increasing mass of the star, a third zone occurs, which is called the 'radiative zone'. In this region the heat is so intense, that thermal radiation is sufficient to transport energy. Some atoms are not fully ionized and can store energy, which is transported by gamma rays from the nuclear fusion process in the core. This transports energy very slowly outward (in our sun, the average time needed is about 170,000 years).

In middle size stars like our sun, the inner core is surrounded by a radiative zone with an outer convective zone. Between these zones lies a transition layer ('tachocline').

The outmost zone and the only one directly observable is the ‘photosphere’, where the gas becomes opaque, caused by a decreasing amount of light-absorbing H^-Atoms.

In stars with a mass greater than 1.5 solar masses and core temperatures of about $1.8 \cdot 10^7$ K, the order of zones changes: The convective becomes the inner and the radiative zone the outer one. This is a result of a different hydrogen fusion process inside the core: Stars with a lower mass fuse hydrogen to helium by proton-proton-chain reactions. Inside a massive star, fusion occurs primarily via the carbon-nitrogen-oxygen-cycle, which starts at temperatures of about 1.3×10^7 K.

The temperature sensitivity of this reaction leads to a steep temperature gradient which results into convection processes in the core. At larger distances from the core, the temperature gradient becomes less steep, but the temperature itself stays high, so that nearly all hydrogen is ionized. This plasma is transparent, and forms a radiative zone, surrounding the convective zone within.

2. Gravitational collapse and supernova

A useful graph for stellar evolution is the Hertzsprung-Russell diagram, which shows the relation between a star’s luminosity and its spectral type (which depends upon the effective temperature). The distinct classes of mainsequence stars, giants and white dwarfs represent different stages in the evolution of stars.

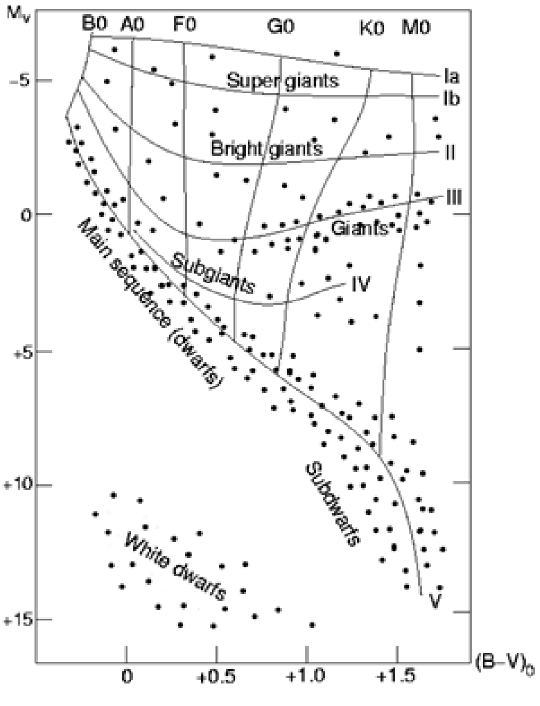

FIG 1. 3 Schematic Hertzsprung-Rusell diagram

A star spends 90 % of its lifetime on the main sequence of the Hertzsprung-Russell diagram, powered by nuclear fusion in its core. Over the millions or billions of years, the supply of hydrogen decreases whereas the amount of fused helium increases. This accumulation of helium occurs the faster the larger and hotter a star is. The increasing amount of helium finally leads to gravitational self-compression which results in further heating of the star. If the core temperature exceeds 10^8 K helium fusion begins.

Stars with a mass below 0.5 solar masses never reach the necessary temperature for helium fusion. But as they fuse their hydrogen so slowly, they have a life expectancy which exceeds the current age of the universe of 13.7 billion years. Therefore no low-mass star in its final stage has yet been observed and it is still unknown what happens after such a star ceases to fuse hydrogen. The table below shows that with increasing mass, the life-expectancy rapidly drops, so that a 10 solar mass star has less than $1/10\,000$ of the life-expectancy of a 0,1 solar mass star.

Mass in $M_\odot$	**Lifetime in years**
30 $M_\odot$	5×10^6 years
15 $M_\odot$	10×10^6 years
10 $M_\odot$	20×10^6 years
5 $M_\odot$	70×10^6 years
1 $M_\odot$	10×10^9 years
0,1 $M_\odot$	300×10^9 years

For more massive stars, the further collapse is entirely dominated by its mass. Once all hydrogen in the core is spent, helium burning will begin, while hydrogen burning continues in a surrounding shell. Hydrogen and helium fusion sustain the star for the most time on the main sequence. During helium fusion, a carbon core is formed, in which carbon fusion takes place after helium is spent. Each time after another element is spent, the star will contract under its gravitational pressure, until the heat in the core suffices for the fusion of the next element. As one element after the other is synthesized, the elements form concentric shells around the core, in which they continue fusion. In the core, high amounts of gamma rays are produced, which create electron-positron pairs, that produce neutrino pairs as they annihilate. The amount of these escaping neutrinos increases with the temperatures in the core, which leads to a massive acceleration of the succession of the burning stages: While carbon lasts several thousand years, oxygen lasts only a year and silicon only a week. How far the star can go in its fusion process, depends on its mass: Low-mass stars with less than 0.5 solar masses are not able to fuse helium after it has exhausted its hydrogen in the core, as its outer envelope simply is not massive enough and can therefore not provide enough gravitational pressure, that could lead to the necessary rise in temperature. These stars are called red dwarfs and there life expectancy can reach 10 trillion years.

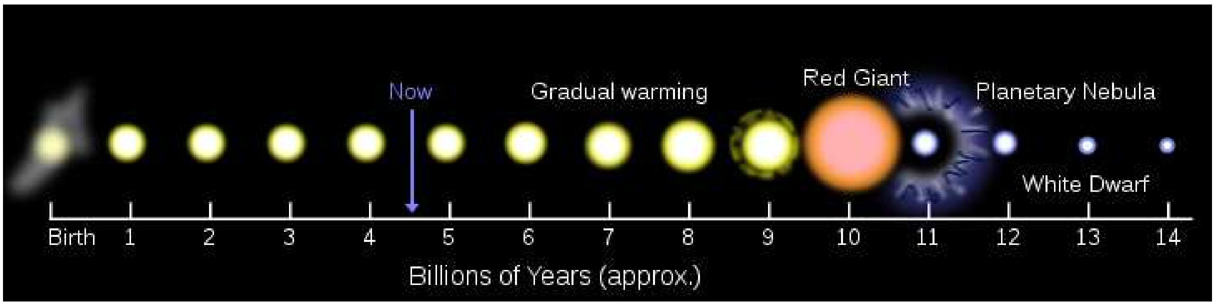

FIG 1. 4 The life-cycle of our sun and its endstage as a white dwarf.

In more massive stars (up to a few solar masses) the outer layers will expand, due to the accelerated fusion processes in the hydrogen-layers around the core. They therefore relieve the core of some of the gravitational pressure which causes it to cool and the star becomes redder. The star leaves the main sequence path on the Hertzsprung-Russell-diagram and becomes a red giant. As the hydrogen in the layer around the core is consumed, the resulting helium is absorbed by the core, which causes the core to extract further and thus accelerating hydrogen fusion. The moment temperature and pressure in the core enable helium fusion, a helium flash occurs in less massive stars, which causes the core to expand and then to contract further, as a result of the loss of energy. After the helium has been consumed in the core, which then consists of carbon and oxygen, fusion continues in a shell around it. As helium fusion is highly sensitive to temperature, pulsations created by instabilities can eventually eject the outer layers, which then form a planetary nebula, surrounding the dying star.

FIG 1. 5 The Helix Nebula is formed of the glowing outer shell of plasma and gas of a star in its end stage.

Extremely massive stars (above 40 solar masses) eject mass very rapidly in their strong stellar winds, and therefore tend to lose their outer layers before they can extend to red giants (this also limits the maximum star mass to 120 solar masses – above it would lose its outer layers by the extreme radiation). If the mass is sufficiently high enough, then after hydrogen and helium fusion took place, carbon, neon, oxygen, silicon and finally iron fusion take place in the core and in onion-like layers around it. Once iron-56 is reached, the fusion process is no longer exothermic and the star cannot gain further energy to sustain hydrostatic equilibrium. If the core's mass exceeds 1.4 solar masses, it will then undergo a sudden, catastrophic collapse. The outer layers fall rapidly inward unto the core were they rebound. Highly energetic neutrinos are produced which fragment nuclei and release nucleons, and which amplify the shock wave of the rebounding matter with their energy. During this, some nuclei catch the released nucleons and form heavier-than-iron elements – up to uranium and possibly even beyond.

Depending upon their initial mass, stars form white dwarfs, neutron stars or black holes as their remnants. However, some of the most massive stars can even be entirely destroyed by a violent supernova that greatly exceeds their gravitational binding energy.

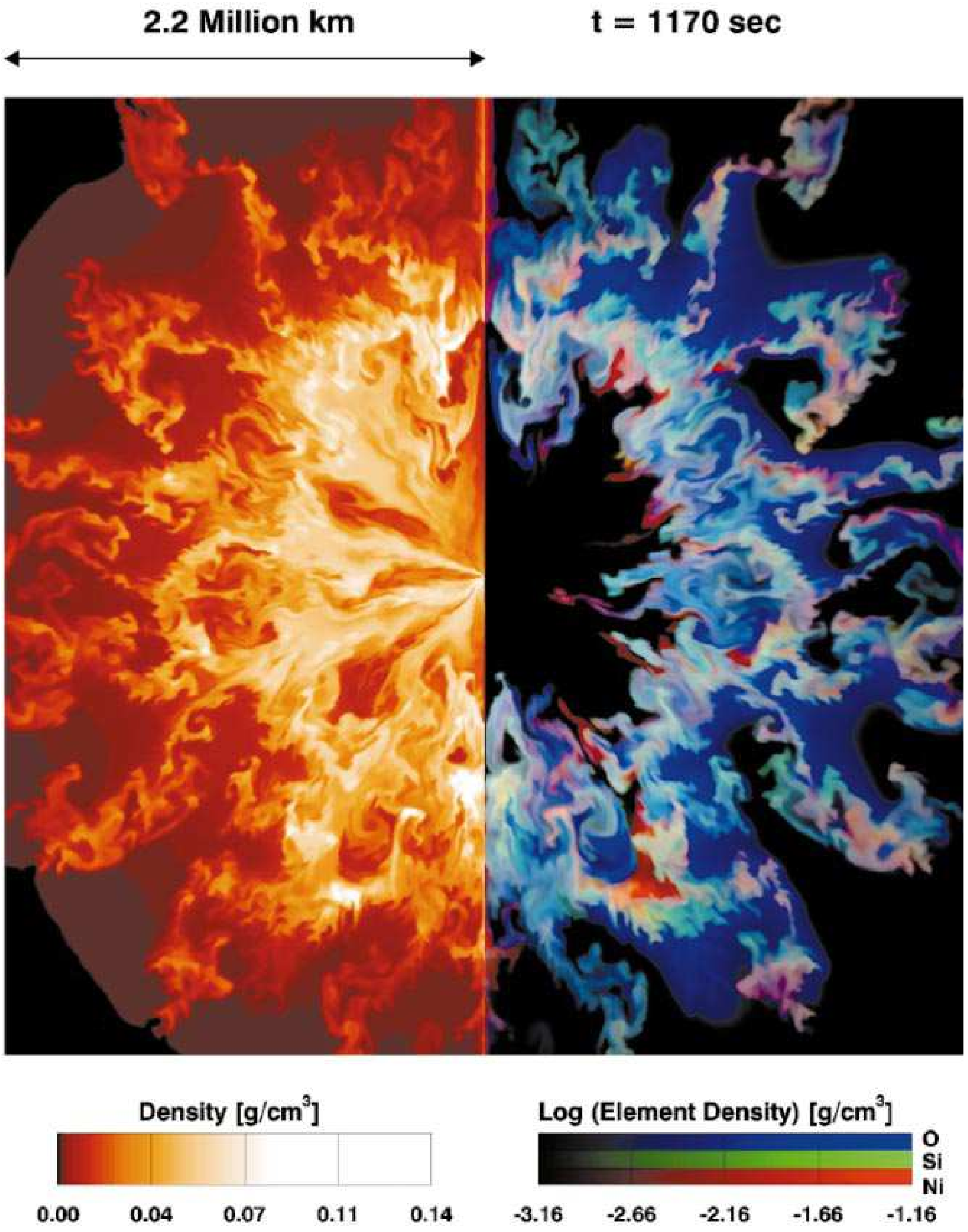

FIG 1. 6 Simulation of the supernova of a red supergiant with 15 solar masses.

3. Star remnants

After the end of nuclear fusion, the core of the star has no energy source to support enough pressure against gravitational forces. It therefore contracts under its own gravity until it reaches a density of 10^7 kg m^{-3}. At that moment the quantum nature of electrons becomes decisive: They have to obey the Pauli Exclusion Principle and therefore cannot be compressed unlimitedly. Additionally, with rising density the position of an electron becomes extremely well-defined. On account of the Heisenberg uncertainty principle, this certainty of position must lead to a high uncertainty in the particle’s momentum. Once the movements of the electrons caused by these quantum mechanical effects dominate over their thermal movements, this condition of matter is called electron degeneracy.

Electron degeneracy pressure supports the star remnant against gravitational collapse and stabilizes it to form a white dwarf, the end stage of 97% of all stars. After a white dwarf has been formed, it will gradually radiate and therefore cool until it becomes a black dwarf, a cold and hardly visible object. The life expectancy of these black dwarfs is thought to be at least 10^{32} years, the current estimation of the lifetime of a proton, until it possibly decays by quantum gravitational processes.

The progenitors of white dwarfs, low-mass stars typically attain a great age before they enter the dwarf stage. Our Sun for example, is 4.5×10^9 years old and is expected to live another 7.5×10^9 years before collapsing to a white dwarf.

Stars above eight solar masses evolve more rapidly: Additionally the thermonuclear reactions proceed further and the star becomes even hotter until it expands into a super red giant. In the central regions of the star, reactions burn until the iron end point. The core is supported against collapse only by the pressure of degenerate nonrelativistic electrons. Similar to lighter stars, nuclear burning continues in surrounding shells of silicon, oxygen, neon, carbon, helium and hydrogen overlying the now inert, central region of iron. Gravity compresses the core to such a density that electrons become relativistic. The pressure they provide now increases less rapidly with increasing density than was the case at the earlier stage when the electrons were nonrelativistic. Moreover, the kinetic energies of electrons have reached a point that the capture on protons – inverse beta decay – produces an energetically more favorable state. The supporting electron pressure is thus diminished below the point at which it can support further growth in the mass of the iron core against gravity. The core has attained its maximum possible mass of about 1,4 solar masses (the Chandrasekhar mass, named after S. Chandrasekhar who first discovered the limit for an object supported by the pressure of ultralrelativistic, degenerate electrons).

The core then commences a rapid implosion taking less than a second. It becomes extremely hot, attaining temperatures toward the end of collapse of the order of tens of MeV (about 10^{11} K). The core is bloated with energetic neutrinos produced by inverse beta decay in the continued neutronization of the core material during collapse. (The cross-section for the interaction of energetic neutrinos and nuclei at densities of 10^{12} gm/cm^3 is sufficiently large as to trap the neutrinos by collisions in the imploding core. They are swept along with the falling material. Moreover, neutrino pairs are created in great abundance by photoproduction (two photons create a neutrino and an anti-neutrino) as the collapsing core attains temperatures of tens of MeV. As the core matter is crushed to high density, the Fermi energy of the thermalized electrons and neutrinos rises. Their pressure, together perhaps with the short-range repulsion between nucleons, resists further compression and a neutron star is formed.

If the mass of the star remnant is extremely high (core mass between 2 – 3 solar masses), gravity can overcome Fermi pressure and the star collapses below its Schwarzschild radius and forms a black hole. However, as the core-collapse and supernova processes are still imperfectly understood, it is not clear whether the collapse to a black hole produces a visible supernova.

If in the most massive stars the energy released in the supernova greatly exceeds the gravitational binding energy, it can be entirely destroyed by the nova, leaving no remnant behind.

II. Properties of Compact Objects

1. White Dwarfs

White dwarfs are the remnants of less massive stars which make up over 97% of all stars in our galaxy. They form out of the core of the collapsing low mass star after it has shed off its outer layers, which turn into a planetary nebula by thermal expansion. As the original star's energy source, which provided enough thermal and radiation pressure to withstand the gravitational forces, has ceased, the core collapses under its own gravity and is then only upheld by electron degeneracy pressure.

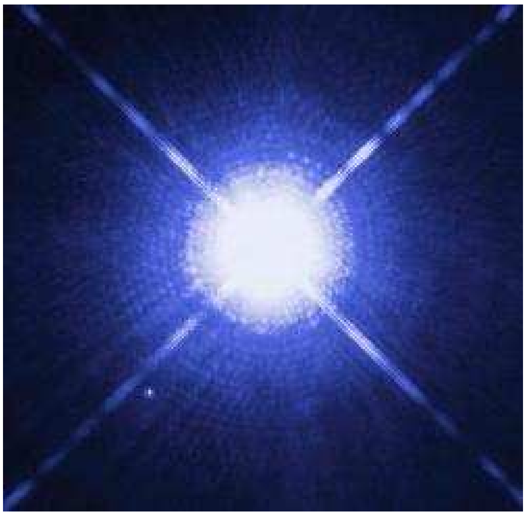

FIG 2. 1 A Hubble-image of the bright Sirius A with its smaller companion Sirius B, a white dwarf (the little white spot on the lower left).

The composition of the white dwarf depends upon the mass of the former star: If the red giant had insufficient mass (below 4 solarmasses) to provide the required 6×10^8 K of core temperature for carbon fusion, the core will mainly consist of carbon and oxygen, which build up during helium fusion. Stars between 4 and 8 solar masses achieve the temperatures necessary for carbon fusion but not for neon, and form oxygen-neon-magnesium white dwarfs as their remnants. Their core mass is reduced by enormous mass losses, as it would otherwise exceed the Chandrasekhar limit of 1,4 solar masses. White dwarfs are enclosed by a thin atmosphere of lighter elements, as heavier elements gradually sink to the surface. Theoretical models suggest that white dwarfs have an outer crust, about 50 km deep with a crystalline lattice underneath (for carbon-oxygen white dwarfs this is very similar to the chemical structure and composition of a diamond).

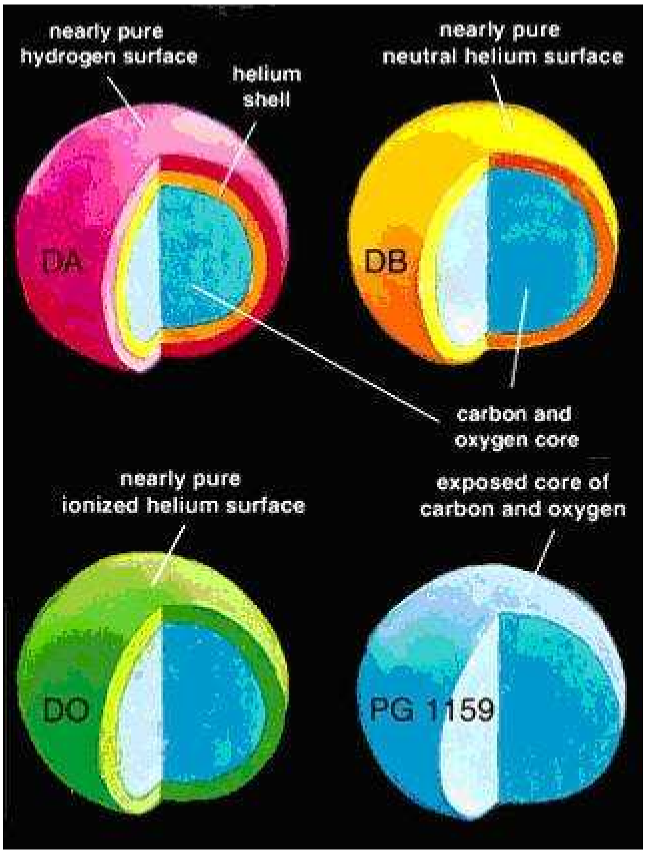

FIG 2. 2 Composition and internal structure for different types of white dwarfs.

2. Neutron Stars

Only two years after the neutron had been discovered by James Chadwick at the Cavendish Laboratory in 1931, Walter Baade and Fritz Zwicky proposed an end stage for star cores above the Chandrasekhar-limit of 1,44 solar masses: The neutron star, which is upheld by neutron degeneracy pressure and has a density comparable to atomic nuclei. In 1937 Oppenheimer and Volkoff devised a theoretical model for a neutron star and the surprising discovery of the first pulsar by Jocelyn Bell and Antony Hewish in 1967 provided the first evidence for their existence.

Neutron stars have a mass between 1.35 and 2.1 solar masses while having radius of only 12 km. Their density corresponds to that of nuclear matter and reaches from below 1×10^9 kg/m^3 near the outer crust to 7×10^{17} kg/m^3 deeper inside.

The inner structure of neutron stars is a topic of ongoing debate, as the state of matter under these extremely high densities is currently not well understood.

It has been proposed, that near the surface, the solid crust of a neutron star consists of a rigid crystalline lattice of iron nuclei. With increasing density electrons and protons tend to combine and form unusually neutron-rich heavy nuclei. Whereas in normal matter the number of neutrons N and the number of protons Z are about equal ($N \approx Z$), the proportion in heavy nuclei is about $N \approx 2Z$.

Above a density of 4×10^{11} g cm^{-3} the large nuclei become unstable and dissolve into a neutron fluid (‘neutron drip point’).

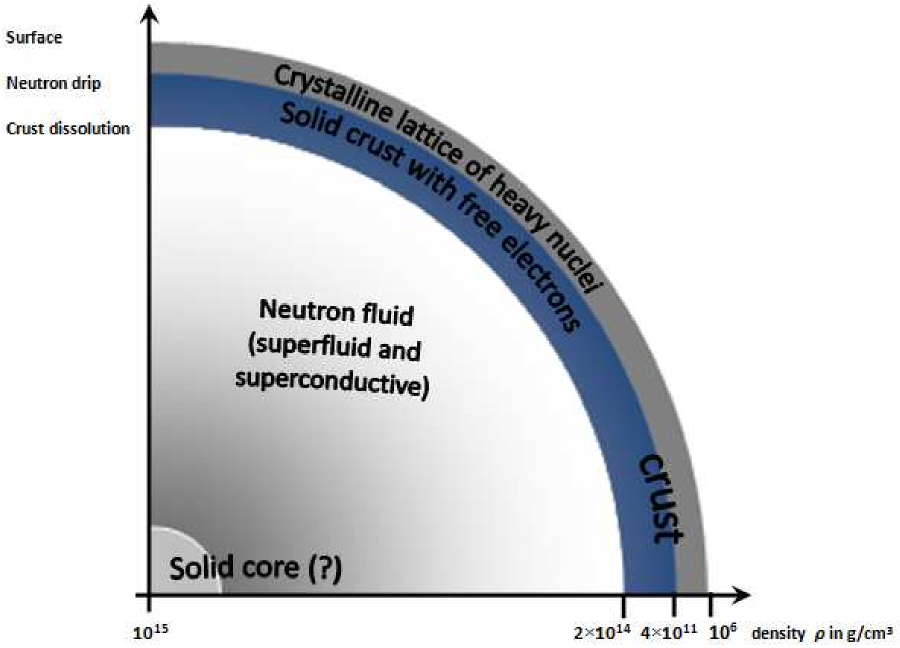

FIG 2. 3 Proposed inner structure of a neutron star

This crustal neutron fluid is superconductive and superfluid and as it can move independently of the rest of the star, it has its own angular momentum and rotates at a different rate.

The interior neutron fluid however always moves at the same angular momentum, as both are coupled by the magnetic field of the star.

At the supernuclear densities in the central regions, exotic states of matter might exist. An inner sphere of quark matter surrounded by a crystalline region of mixed phase hadronic and quark matter has been proposed, as well as a solid core consisting of mesons, kaons or pions, which were formed under the enormous pressure of 10^{15} g cm^{-3} (corresponding to the mass of 30 Giza pyramids in the volume of a sugar cube). Another possibility is the existence of quark matter not bound into hadrons (commonly referred to as quark-gluon-plasma or QGP). However, as a mathematical description of this state of matter can only be correctly described by the complicate means of quantum chromodynamics, a full understanding of the interior processes inside neutron stars is out of reach for current computer simulation technology (recently, the QCD processes inside only one proton were correctly described for the first time).

3. Black Holes

A black hole is a region of space with highly deformed space-time, from which at a certain distance nothing, not even light can escape. This distance is called the event horizon and encloses the black hole.

In 1930, Subrahmanyan Chandrasekhar calculated that a star remnant above 1,44 solar masses would inevitably collapse and form a black hole. It was later found out, that neutron degeneracy pressure can stabilize stars above the Chandrasekhar mass limit, but stars above 3 - 4 solar masses (the Tolman-Oppenheimer-Volkoff limit) must inevitably collapse, as there is no known mechanism that is powerful enough to compensate the gravitational forces.

Though black holes cannot be directly observed, their existence can inferred by tracking the path of orbiting stars or by large amounts of radiation, which are emitted, when an accretion disc forms around the black hole and is heated to high temperatures as it flows inward. Aside from stellar black holes, galaxies with very luminous centers have been observed (so-called Active Galaxies) which provide evidence that the radiation is emitted from an accretion disc around a very massive black hole. These black holes are estimated to have masses between 10^6 and 10^{10} solar masses, and it is currently not clear how they formed. In most galaxies, including our own, evidence for giant black holes at the center was found and it is thought that these play a major role in the formation of galaxies.

4. Hypothetical Quark Stars

Currently no known physical process could prevent a star remnant above the Tolman-Oppenheimer-Volkoff limit to collapse to a black hole. However it has been proposed that under sufficient pressure, the neutron-degenerate matter inside a neutron star breaks up into its constituent quarks. Some of these become strange quarks and form together with the up- and down-quarks a “quark star”, which is similar to a giant hadron, that is hold together by gravity instead of the strong force. These stars would strongly resemble neutron stars, which makes them hard to detect and no conclusive evidence has been found yet.

5. Relativistic effects

Though effects predicted by the Special and General Theory of Relativity are normally irrelevant for normal stars, they gain in importance for their compact remnants. While white dwarfs are barely relativistic, relativistic effects have a moderate relevance for neutron stars, but play an important role in black holes.

Due to the time dilation in a gravitational well, light becomes red-shifted near a compact object. Therefore black hole never seems to “finally” collapse for an outward observer: The star will simply become more compact and red-shifted, until the light is so extremely red-shifted, that the star remnant appears black. Therefore black holes were first called “frozen stars”, although this depends on the reference frame: An in falling observer could experience all phenomena associated with a “finally collapsed” black-hole.

Additionally, light is bent in the vicinity of compact objects, which would make it theoretically possible for an observer of one side of a neutron star, to also see some parts on the other side. An observer who looks tangential to the “surface” of the event horizon of a black hole while falling inwards, could even see himself in the distance, as light reflected from his back can be so extremely bent by the black hole, that it can travel around it.

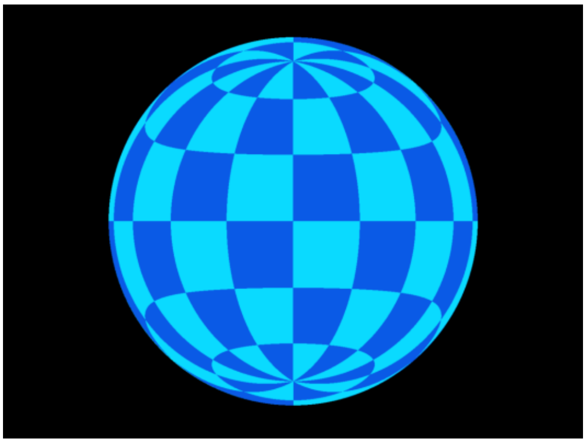

FIG 2. 4 In a strong gravitational field light is extremely bended, and therefore an observer can see the back of the checkered sphere.

The General Theory of Relativity also predicts, that compact rotating objects drag space-time with them, a phenomenon called “Frame-dragging”. It is derived from gravitomagnetism, an approximation of field effects based upon the mathematical analogy between Maxwell's equations and the Einstein field equations.

Though direct evidence for frame-dragging could not be gained yet, relativistic jets from Active Galaxies could be explained by gravitomagnetic forces within the frame-dragging region of a rotating black hole, that deform magnetic field lines.

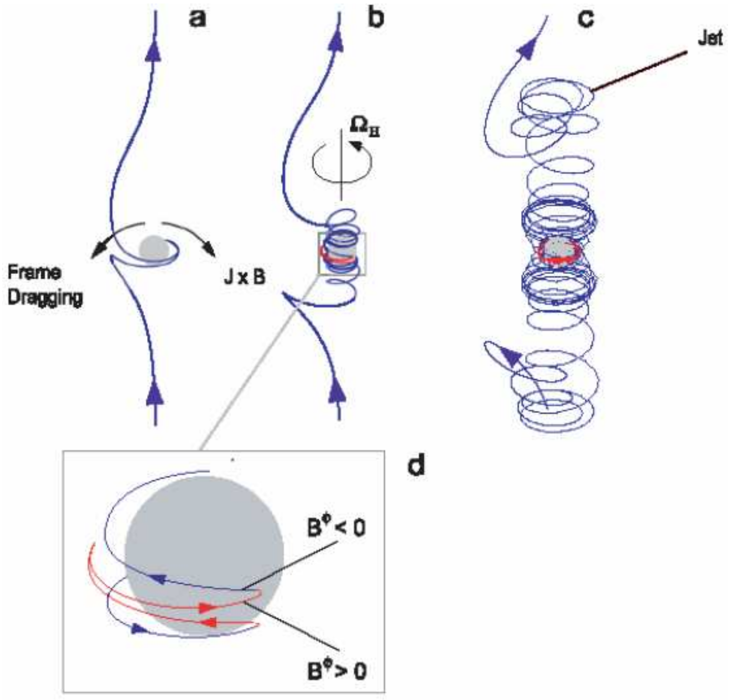

FIG 2. 5 Simulation of the twisting of the magnetic field in close proximity to a black hole due to „frame-dragging“ effects. Note the resulting jet formation.

III. Plasma Physics

1. Basics

A plasma is a gas which consists of a certain amount of charged particles. It can be seen as a fourth state of matter and it is by far the most common: 99% of all visible matter in the universe is thought to exist in the plasma phase. Due to the charged particles, plasmas respond strongly to electromagnetic fields and develop a complex behavior, which is described by Magnetohydrodynamics.

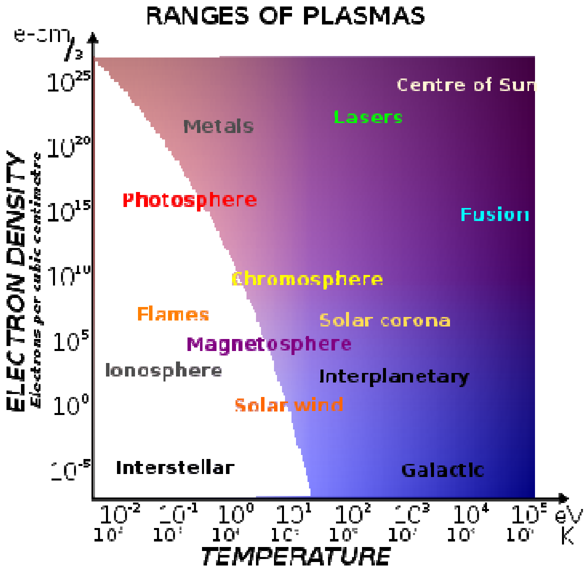

FIG 3. 1 Plasma plays an important role in a wide variety of astrophysical phenomena.

An important characteristic of a plasma is the Debye-length, which indicates the distance after which a charged test particle will appear neutral to the surrounding plasma, as oppositely charged particles gather around it and “shield of” its electric field. In a plasma oscillations can occur: Consider the ions being rigidly held in place, with freely moving electrons that hold constant distance with respect to each other. If the electrons are displaced for a certain distance, they will be pulled back by an electric field. Therefore they will gain kinetic energy and will overshoot, when the force by the electric field equals zero. Then a harmonic oscillation can occur, whose frequency is called electron plasma frequency.

2. Single Particle Motion in a magnetic field

As a plasma consists of many charged particles with their own electric and magnetic fields, the exact dynamics can be very complicated, though the motion of a single charged particle in a magnetic field is well defined.

A single particle which travels perpendicular to a magnetic field and an electric field, which are also perpendicular relative to each other, will gyrate along its path, clockwise if it is positively, anti-clockwise, when it is negatively charged (B). Its motion consists then of the circular gyroscope motion and a drift velocity in its original direction of motion, which is independent of charge and mass. If the magnetic field changes through space or in time, the drift changes accordingly to the changing “magnetic pressure”. This pressure is of course only a fictious force: Once the particle experiences the change in the magnetic field, its drift speed changes, and this acceleration can be seen as the result of the fictious force of “magnetic pressure”. Ions and electrons will travel in opposite directions, and therefore a net current results in the plasma (D). Apart from this “grad-B-drift”, a “curvature-drift” may occur, if the particles move along curved magnetic field lines, while gyrating about them. The particles are unable to move across the field lines, due to resisting forces and experience a centrifugal force by the curvature of the field line. If the electric field changes over time, this results in a polarization-drift, and the drift perpendicular to the electric and magnetic field (which are also perpendicular to each other) will increase over time, if the electric field increases.

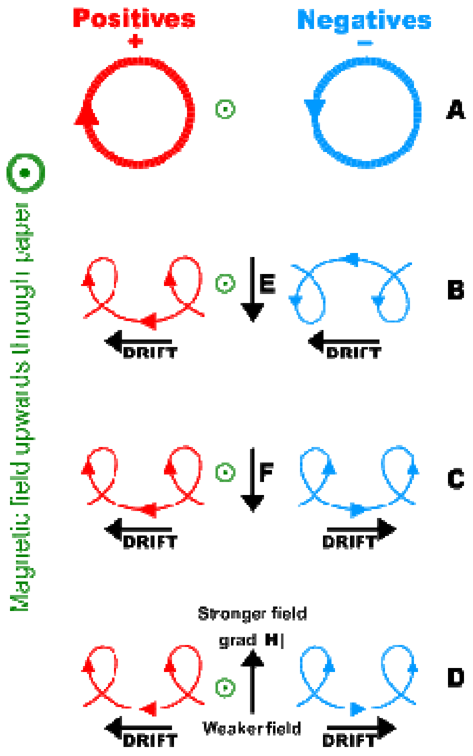

FIG 3. 2 Particle motion of charged particles in a magnetic field (A) without an additional perpendicular field or force, (B) with a constant, perpendicular electric field, (C) with a perpendicular force, (D) with a changing magnetic field.

Apart from these forces perpendicular to the field lines, forces along the field lines are important as well. Consider a magnetic field that has a “bottleneck” as shown in Fig. 3.3. Whether a particle can go past this "bottleneck" or is reflected, depends on its initial kinetic energy and its pitch angle. If the magnetic field has two of these bottlenecks, this configuration is called a "mirror machine", as charged particles can be constantly reflected from the ends and therefore trapped within.

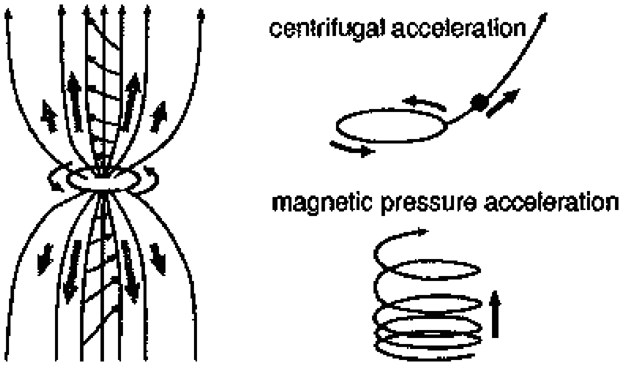

FIG 3. 3 Magnetic „bottleneck"

3. Interaction of plasma flows with magnetic fields – the aurora as an example

Due to their abundance, plasmas play an important role in a wide variety of astrophysical phenomena.

Understanding of the Magnetohydrodynamics in weak magnetic fields and at subrelativistic velocities in the Aurora in the polar regions of Earth illustrates several basic principles but also the dynamical aspect of plasma-magnetic field interaction and might prove to be helpful in understanding the electrodynamics of pulsars, which will be introduced in the subsequent chapter.

The Aurora is created by charged particles from the solar wind (a low-density plasma), and the reaction with atmospherical molecules and the magnetic field of Earth.

Moreover radiation-belts, the magnetic field itself, ring currents, and the magnetic field of the incoming plasma combine to a highly complex process, which is still not well understood. The incoming plasma is definitely subrelativistic (400 km/s), has a low density (ca. 5 ions/cm^3) and interacts with a very low magnetic field.

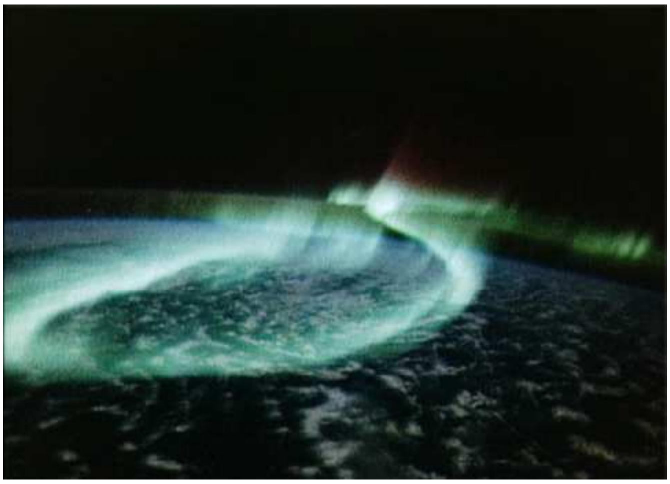

FIG 3. 4 Aurora australis as seen by the crew of the STS-39 Space Shuttle mission

Auroras are accompanied by strong radio emission: If it were not deflected by the ionosphere, radio broadcast would be impossible: Strong radio emission, so-called auroral kilometric radiation (AKR) in the 5 - 500 kHz frequency range with a power output of up to 1000 MW outruns a radio station with a typical power output (the so-called effective radiated power) of about 0,1 MW.

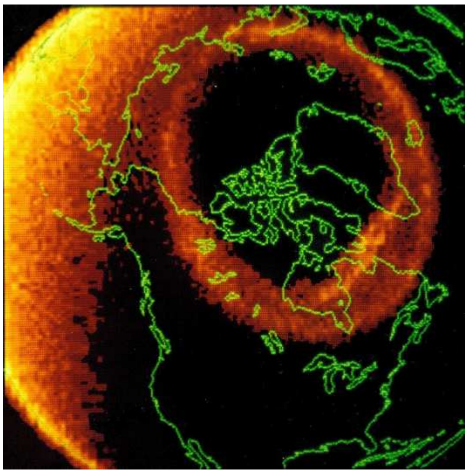

FIG 3. 5 The spatial distribution of the auroral oval in ultraviolet wavelengths. The noncircular distribution results from the non-dipolar components of the magnetic field. Note that the center of the oval is the geomagnetical South Pole near Ellesmere Island in Northern Canada.

Auroras are created in a well-defined oval ring around each of the magnetic polar-regions, with thin sheet beams of energetic electrons forming along the geomagnetic field lines, giving the aurora a curtain-shaped form (besides merely faint glows, which are also seen). As the Cluster mission in 2008 has shown, the radio emission is sent out in a plane tangent to the magnetic field lines at its source.

Apart from radio-emission, auroral phenomena also emit EUV (Extreme Ultra-Violet), UV, visible and IR emissions, which are created by electrical discharge and associated photochemical processes, when charged particles enter the atmosphere and interact with molecules (as O, N, O_2, N_2, NO, NO_2, OH, etc.). The common colorful glow in the aurora is created by energetic electrons (e^*) which collide with nitrogen molecules (N_2) , excite and ionize them.

$$N_2 + e^* \rightarrow N_2^+ + e^* + e$$

If the nitrogen molecules regain an electron after the ionization, it emits photons in the blue color range. The return from an excited state to the ground state is typically associated with emissions in the red color range. As a small amount of energy of the energetic electrons is invested in the ionization and excitation of the molecules, the resulting secondary electrons are highly energetic as well. They excite oxygen atoms, which emit green or brownish-red light as they return to their ground states, depending upon the energy absorbed.

As it was already mentioned, the dynamo which powers the aurora is driven by a constant flow of plasma, the solar wind, which interacts with the magnetic field of the earth and creates its magnetosphere, in which a complex dynamo-process takes place.

Dynamo processes in general are created when an electrical conductor moves relative to a magnetic field, whose field lines are orthogonal to the movement of the conductor. Due to the Lorentz force, an electrical current is induced. Plasma, like the solar wind conducts electric currents but effectively only along magnetic field lines (along which the particles gyroscope), less effectively perpendicular to them. Therefore a temporary magnetic connection of the plasma's field lines to the geomagnetic field line occurs, a phenomenon that is called "magnetic reconnection".

The solar wind consists mostly of protons and electrons, a plasma which originates from the corona, the sun's outermost layer. It travels with super-magnetosonic[1] speed with respect to the earth and a shock wave (the "bow shock") is formed. As

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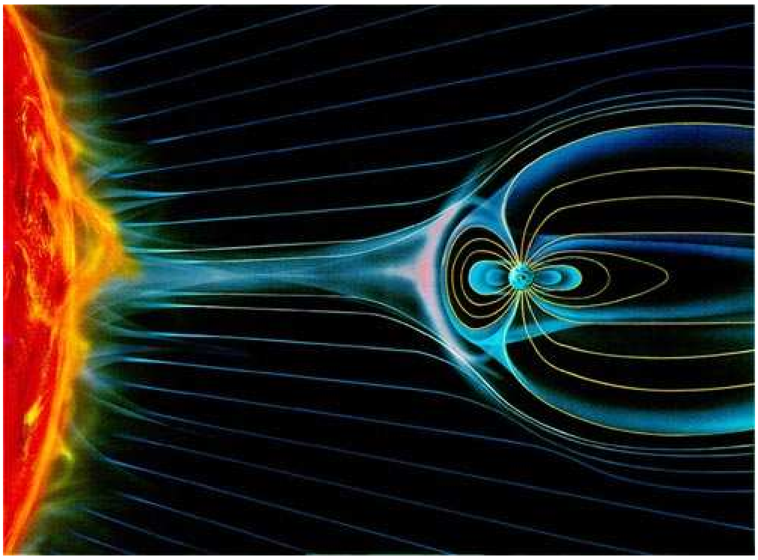
[1] Like in air, where pressure and density differences travel at the speed of sound, pressure and density differences in magnetized plasma travel with magnetosonic speed.

the solar wind flows through the shock wave it is slowed down, until its pressure is balanced by the magnetic field. The boundary of this pressure balance is called the magnetopause. When it reaches the Earth's magnetic field, it is diverted in a "bow shock", whereby some particles travel along the magnetic field lines, while others are trapped in radiation belts, like the well-known Van Allen belts. On the night side a long magneto-tail forms, giving the magnetosphere a teardrop-like shape.



The trapped particles form ring currents, as electrons are diverted to eastside and protons to the Westside and therefore induce a potential difference. The other charged particles which travel along the field lines create auroras around the poles. However, perturbations in the solar wind – for example during a flare - can lead to changes in the aurora. Otherwise perturbations in the geomagnetic field (so-called "geomagnetic storms"), triggered by auroras can lead to a sudden release of the trapped particles, which amplify the aurora.

The radio emission is cyclotron radiation, emitted from highly energetic charged particles like electrons, while they gyroscope along the geomagnetic field lines. However, if they approach a "mirror point", their spiral motion tightens until it becomes circular and they spiral back into the opposite direction. Therefore the electrons can carry only a limited amount of current. As the dynamo power increases, a potential drop of several kV develops, which allows the electrons to gain enough energy to pass the mirror point and excite atoms and molecules in the upper atmosphere.

The aurora on Jupiter

Apart from Earth, all planets with an atmosphere occasionally show aurora phenomena, though the location and frequency of occurrence is determined by the strength of the magnetic field. While Earth has the strongest magnetic field of all terrestrial planets and its auroras occur around the polar region, the auroras on Mars may also appear near the polar regions. Strong magnetic fields were also detected around Jupiter and Saturn, with Jupiter's having several unusual properties.

As Jupiter spins around every 10 hours, its rotating magnetic field induces an electric field with currents of up to 10 million Volts. While on Earth all auroras are caused by solar winds, Jupiter is not necessarily dependent on the sun's plasma to produce auroras. Charged particles from volcanic winds from its highly volcanically active moon Io reach can reach Jupiter and lead to intense auroras. Jupiters magnetic field is more complex than Earth's, as it includes the moon Io, Ganymed and Europa, with each having an own magnetic field. There seem to be magnetic connection, so-called "flux tubes" between Jupiter and its moons, along which it is thought Io's volcanic winds travel along.

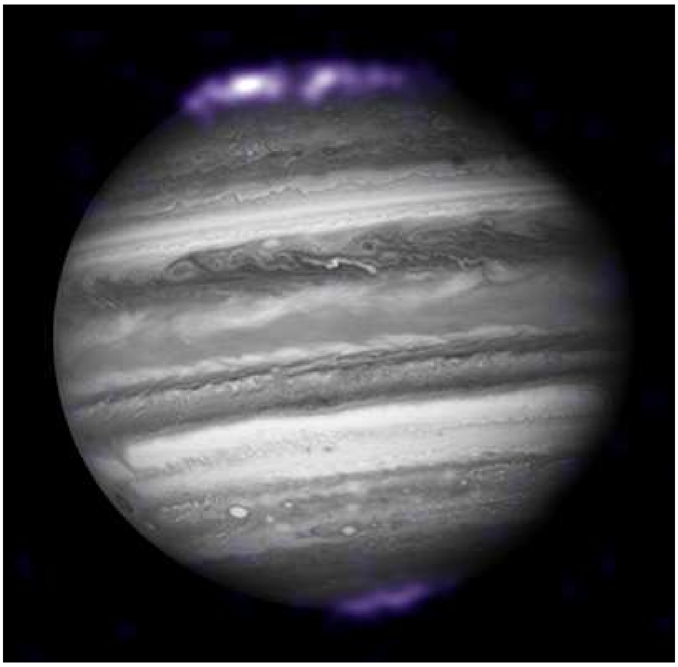


FIG 3. 6 X-ray auroras observed by the Chandra X-ray Observatory overlaid on a simultaneous optical image from the Hubble Space Telescope. These auroras are a hundred times more energetic than those on Earth and larger than our entire planet.

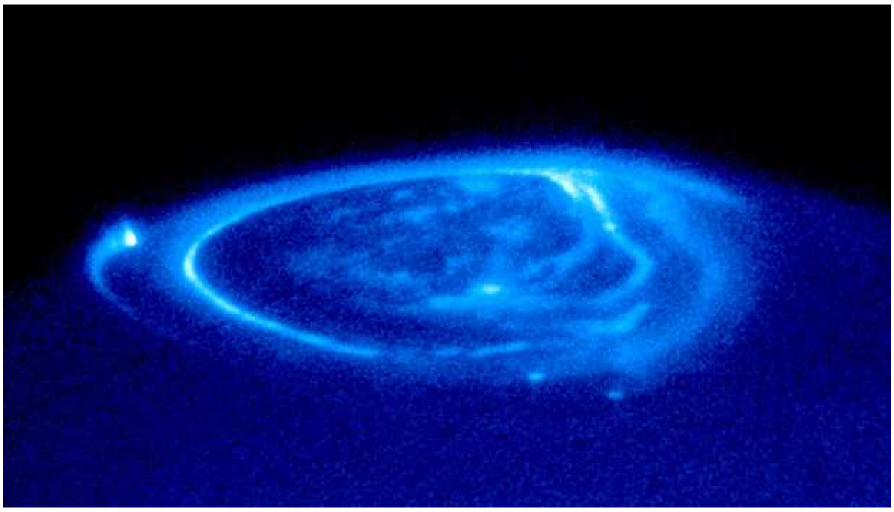


FIG 3. 7 Aurora on Jupiter, imaged by the Space Telescope Imaging Spectrograph aboard the Hubble Space Telescope. Normally the aurora appears red, due to the hydrogen of which Jupiter's atmosphere mainly consists. The bright blue spot on the left is a magnetic connection (a "flux tube") to Io, the two spots on the lower right are (from left to right) to Ganymede and Europa.

FIG 3. 8 A composition of Jupiter with its auroral ring (blue) and the north-polar x-ray source during activity (pink). No corresponding pulsating x-ray source has been found on the South Pole, but that may be due to poor viewing conditions.

When Jupiter's auroras were observed by satellites for the first time, an unusual high emission of x-rays was observed, which was in this amounts not known from terrestrial auroras. First it was thought, that these x-ray emissions were caused by energetic sulphur and oxygen ions from the inner magnetosphere, precipitating to the polar region. They would be therefore directly connected to the auroral activity. However, high-resolution images in 2001 showed that the x-rays originated from a "hot spot" close to the pole and that they "pulsed" with a relatively regular period of 45 minutes. Apart from the strange x-ray emission, unexpected UV- and IR-emissions were also observed. How these highly localized, highly variable emissions over such a wide spectrum are created, is still unknown.

IV. Pulsars

1. The Discovery of Pulsars

The first pulsar was discovered by Jocelyn Bell and Antony Hewish on November 28, 1967 at the Mullard Radio Astronomy Observatory. While conducting a low-frequency survey (81 MHz) looking for the scintillation of quasars in the interplanetary plasma, Jocelyn Bell noticed regular pulses in her observation data. Several years earlier, Pulsar signals had already been recorded by the Jodrell Bank Telescope, but it was thought that they originated from terrestrial interference, as radar or electric fences frequently caused strong impulses. Bell observed however, that the pulses appeared about four minutes earlier every solar day (on time in sidereal days) and that the source therefore had to be from outside the solar system.

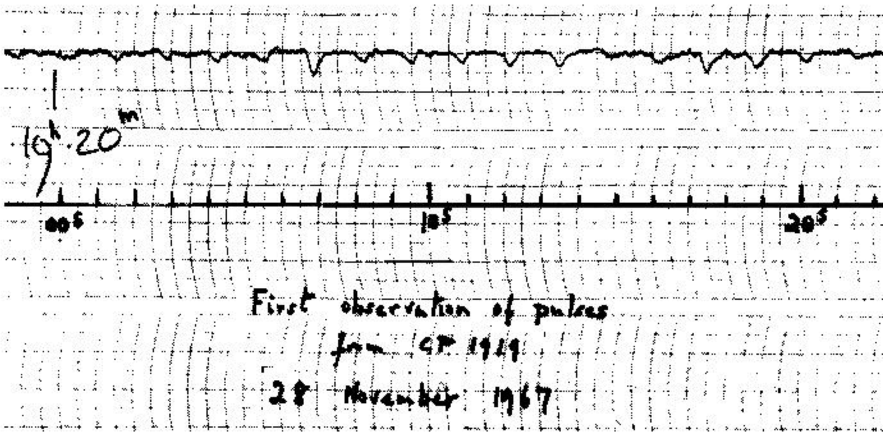


FIG 4. 1 Recording of the first known pulsar, CP 1919 (now known as PSR B1919+21). The periodicity of 1.3 s is clearly visible.

In general, there can be three causes for periodic astronomical phenomena: Orbiting, Pulsation or Rotation. As it is unlikely that pulsation would be regular enough and that an orbiting object would have a sufficiently high velocity, the pulses must originate from a rapidly rotating object, which is small enough so that it is not ripped apart by its rotation. A likely candidate is a neutron star, which has a sufficiently small radius and which could gain enough angular momentum from the previous giant star.The radio waves are then emitted along the magnetic field axis and due to their inclination to the rotational axis, the pulsar’s beacon sweeps through space. When it coincidentally hits Earth, a pulsating radio source is detected. However, the process which emits the radiation in the first place, must be a complex interaction with the strong magnetic field This interpretation was suggested in the discovery paper by Hewish and Bell in 1968 and independently also by Thomas Gold and Franco Pacini in the same year. It was later strongly pursued by the first models for the emission mechanism and remains the most common interpretation today.

2. Basic Features of Pulsar Signals

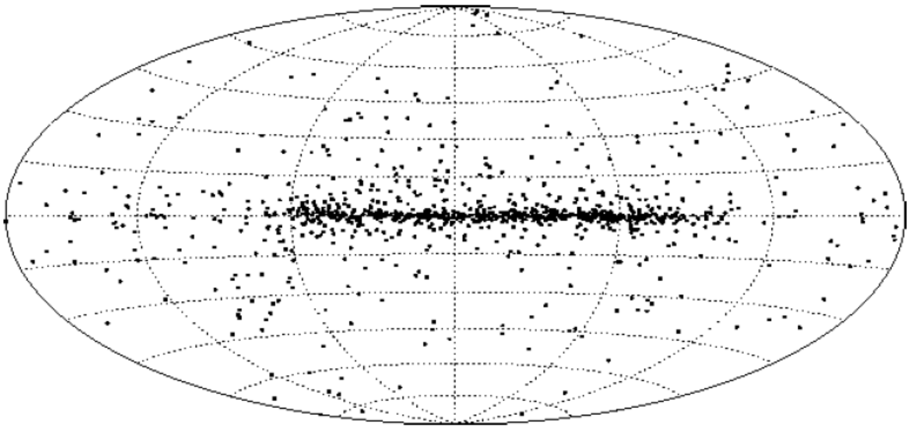


FIG 4. 2 Distribution of known pulsars in galactic coordinates.

At the moment, about 1765 pulsars are known[2], all within our galaxy and with periods between 1 millisecond and 8 seconds. Most Pulsars emit regular radio-pulses and become faint in higher frequencies, while they are difficult to observe at lower frequencies (due to increasing technical problems and interstellar absorption).

However, some pulsars emit mainly x-rays (like Cen X-3) and quite recently the Fermi Gamma-ray Space Telescope even found a regular pulsating source which emits only in gamma-rays. An x-ray-pulsar, XTE J1739-285 is currently also the fastest spinning neutron-star known, with a period of only 0,0009 seconds. Some pulsars, like the Crab and the Vela pulsar show also pulsations in the visible spectrum (“optical pulsars”).

Though the pulse signals are in their periodicity extremely regular, the intensity and shape of the pulsation signal is not, as can be seen in Fig 2. Additionally many

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[2] The overall galactic population is estimated to be about 10^5. This makes pulsars one of the most common astronomical objects, which poses a serious threat to the current models of stellar evolution: As neutron stars are the remnants of giant stars and were generated in a supernova, these giant stellar explosions should occur much more often than observed.

pulsars are observed to slow down (typical timescale about a million years) and those that are not, might change their period too slowly, to be detected. This is another good point to strengthen the assumption, that pulsars are indeed rapidly rotating objects: Orbiting objects, as they lose energy, would fall into lower orbits and the pulse signals would therefore speed up, not slow down.

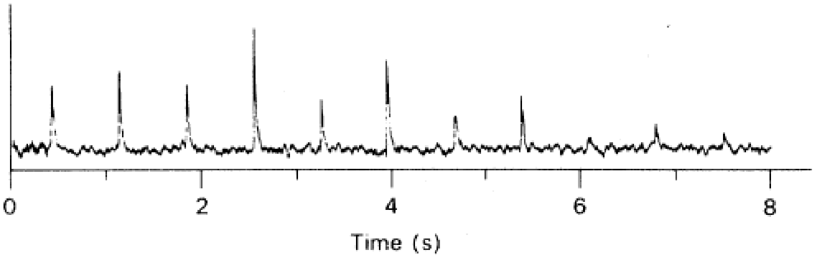


FIG 4. 3 Regular periods, but different shapes and amplitudes in single pulse signals from PSR 0329+24 at 410MHz

But the regularity of the pulses can be temporarily interrupted when a pulsar “nulls”, meaning that the pulse signals becomes undetectable for 10 – 100 pulsar periods and then starts again, with the same periodicity as before. This behavior show about 30% of all known pulsars. In some pulsars, the main pulse is actually composed of several distinct pulses, which is called “drifting”. In the pulsar PSR 1237+25 the overall pulse consists of five distinct pulses, but which cannot be seen in any single pulse, but only in the overall average waveform. Only 5% of all pulsars are drifters, and the drifters which also null, continue the pattern of their subpulses at exactly the same position after the nulling, where it had been before.

Slow pulsars are much more common than fast pulsars, which is natural, if fast pulsars slow down rapidly. For example, the pulsar in the Crab Nebula, which formed in a giant supernova, that was recorded by Chinese and Arab astronomers in 1054 and is therefore quite young, has a period of 0,033 seconds.

If one plots the slowing down rates of pulsars against their current period (on a logarithmic scale, as in Fig 3), one spots a line along which many pulsars lie which null. That suggests that pulsars, as they slow down to longer periods and their slowing down rate changes, null more frequently, staying off for longer periods of time until they finally are off for good.

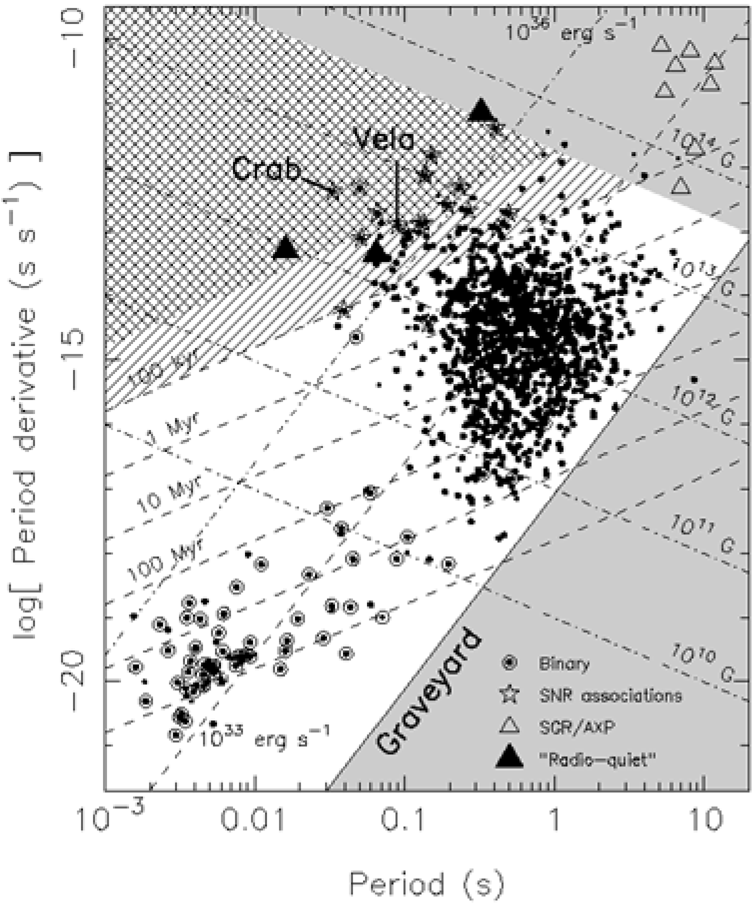


FIG 4. 4 Pulsars plotted in a diagram of their period against their slow down rate. Note the "graveyard"-line.

Apart from these steady slow-down rates, some pulsars show sudden increases in their rotation rate, followed by a slow "recovery", a phenomenon known as "glitches". Glitches are quite rare, and in four decades only 51 pulsars have been observed to perform 170 glitches.

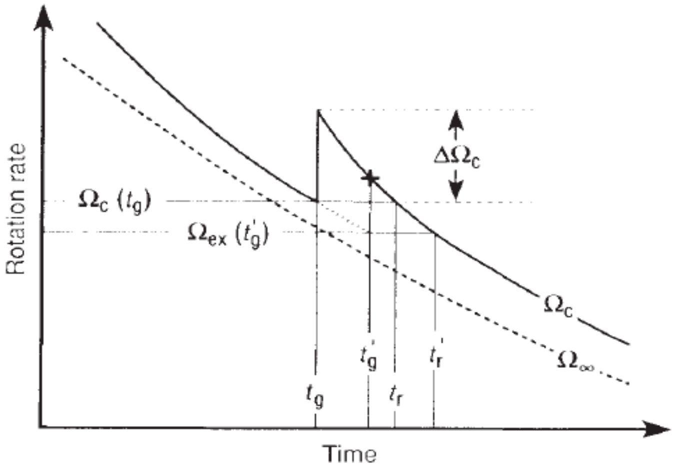
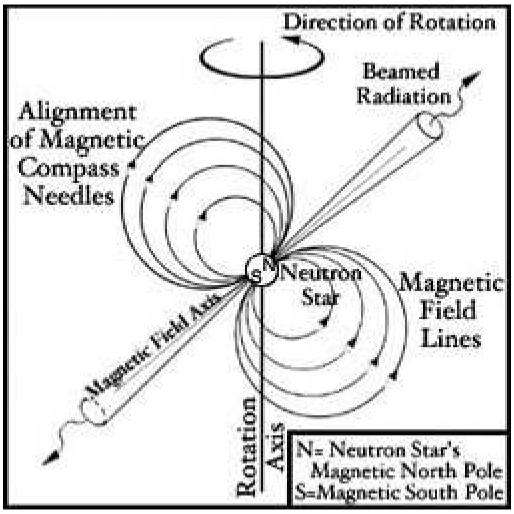


FIG 4. 5 Schematic evolution after a glitch (Link, Epstein, Riper 1992): A glitch occurs at $\mathbf{t_g}$, the pulsar recovers its pre-glitch rotation rate at $\mathbf{t_r}$, and fully recovers at $\mathbf{t_r'}$, when its rotation rate is equal to the one it would have, if the glitch had not occurred. Usually, the slow down rate increases after a glitch.

For the cause of the glitches, planets have been suggested (by Hills and Michel both 1970 and others), but long-term observation showed no periodicities. Later it has been suggested, that abrupt rises in the pulsar rotation rate might be caused by a transfer of angular momentum from the star's solid crust to an interior, faster rotating superfluid (Pines, Alpar 1981).

3. A First, Simple Pulsar Model

The existence of the pulsar signals and the current theory of stellar evolution already provide enough information to synthesize a simple model of a pulsar: The pulsar object is a very small, rapidly spinning neutron star with a magnetical axis inclined to its rotational axis. The received electromagnetic radiation is emitted along the magnetic axis and as the signals are very strong, in spite of the pulsar's distance, the magnetic field has to be extraordinary strong as well.



However the exact mechanism of the emission of radiation must be a complex interaction between the magnetic field, the induced electric field and charged particles - and maybe also depends upon the inclination between the axis and a flow of plasma from outside. In understanding the exact electrodynamics of pulsars, the complex physics of magnetized plasma in a magnetic fields plays a major role. However, these processes are not only found in pulsars, but also in many other astrophysical phenomena, including a process directly visible in the atmosphere of our Earth.

4. Theoretical models for the Pulsar Magnetosphere and Emission Mechanism

The central issue of pulsar theory is to explain what mechanism creates such intense radio emission and how it arises in the formation of the neutron star. Additionally, there is still a lack of a concise categorization of different pulsar types, and an explanation for the observed phenomena, such as “nulling” and “glitches”.

Both models are built on the assumption of the “simple model”, that pulsars are indeed rotating neutron stars with a strong magnetic field.

General properties of the magnetic field

If a star collapses, its angular momentum and its magnetic field are transferred unto the resulting neutron star, and thereby the magnetic flux density and the velocity at the surface increase dramatically, due to the smaller size of the star remnant.

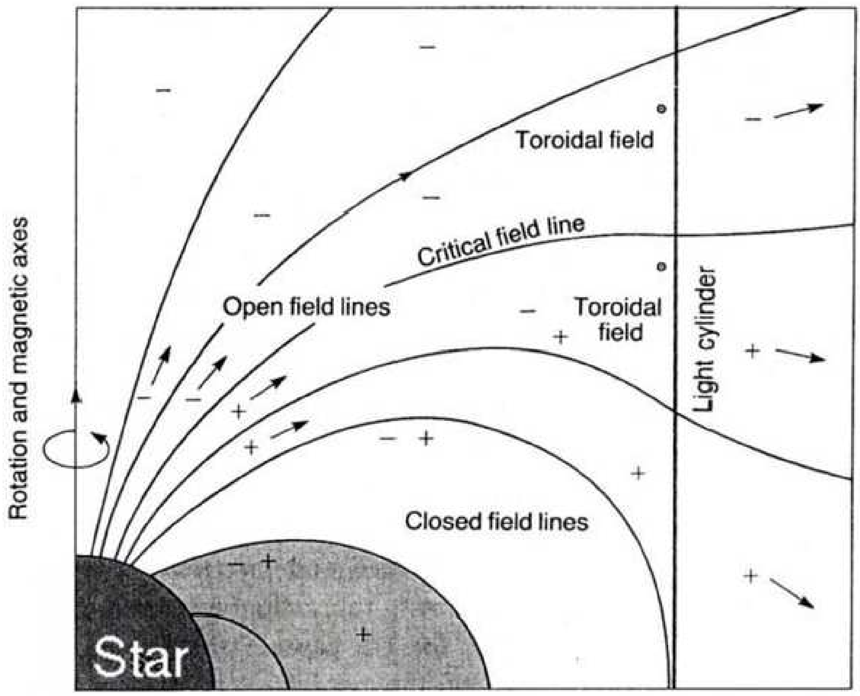
The decay of the magnetic field is comparatively low to the life-time of a pulsar, which is a result of the superfluid interior. Due to the high magnetic field strengths ($\approx 10^4 - 10^9$ tesla at the pole caps) the energy density has a considerable effect on the crystalline structure of the surface (converted into an equivalent mass density this complies with 10^6 kg m^{-3}).

All processes outside the star are dominated by its huge magnetic field, whose axis does not necessarily concordant with the rotational axis of the star. The induced electrostatic forces on an electron near the surface of the Crab pulsar are for example 10^{12} times larger than the gravitational forces. These forces lead to an extraction of particles from the neutron star’s surface, which then fill the surrounding magnetosphere.

The first description of the electromagnetic field of a rotating star was made in 1955 - prior to the discovery of pulsars - by Armin Deutsch and showed the configuration of the field of a magnetic dipole in vacuo. Deutsch pointed out, that that a sufficiently magnetized rotating star will not continue to stay in vacuo, but surround itself with a charge cloud. Goldreich and Julian elaborated this idea in 1969, shortly after Gold suggested that pulsars are magnetized rotating neutron stars. Goldreich and Julian developed an electrodynamical model for the simplified case of an aligned rotator (i. e. a pulsar whose magnetic and rotational axis are aligned).

Goldreich-Julian or Standard Model

As the Goldreich-Julian-Model describes an aligned rotator, which can naturally not lead to the pulsar phenomenon we observe on Earth, it can only illustrate some basic principles and cannot explain the details of pulsar physics.



The central idea of the Goldreich-Julian model is the extraction of particles from the surface and a resulting plasma in the magnetosphere with currents along the field lines.

The presence of the magnetic field of a rotating magnetized sphere will induce an electric field. However, the high conductivity of the magnetosphere along the field lines prevents an electric charging, and no net electric field can be sustained. This condition is similar to the interior of the neutron star, where the superconductive neutron fluid obviates the separation of charges. Therefore the outer magnetic field can be regarded as an extension of the interior.

The particles which are extracted from the surface by the strong electromagnetic forces form a surrounding plasma, charges near the equatorial region and those near the poles will be of opposite charge. As the surrounding plasma experiences the same electromagnetic field as the interior of the neutron star, it is forced to co-rotate with the star ("corotating magnetosphere"). In a specific distance from the star, the plasma speed reaches the speed of light. This limit defines the area of the near zone and its surface is known as the light cylinder.

Goldreich and Julian distinguish between three zones in the region surrounding a pulsar: A near zone, a wind zone and a boundary zone.

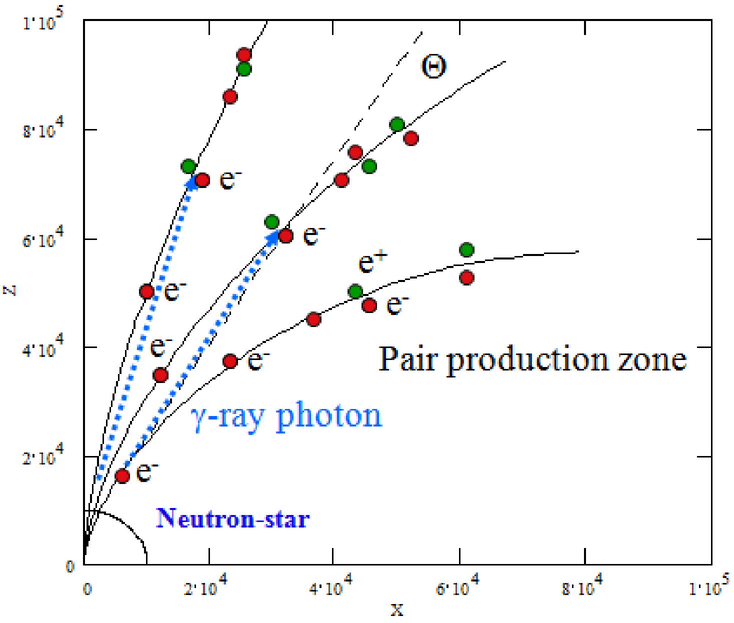
Within the light cylinder, the magnetic field lines are closed, outside the field lines are open (they close in the boundary zone). The open field line region defines the polar caps on the neutron star surface and is confined by the "last open field line".

In the near zone, the magnetic field is provided by the magnetic currents inside the star, whereas in the wind zone, currents due to escaping charges from the star's surface are the main source of the magnetic field. The boundary zone comprises about 90% (by radius) of the supernova cavity. As the interstellar gas is a good conductor, the electric field vanishes outside the supernova cavity.

The emission mechanism

This mechanism was not included in the original Goldreich-Julian-model, but was later added, to explain the observed emission. It is therefore part of the Standard model and the "Standard emission model".

The observed emision is thought to be created by charges which flow along the curved magnetic field lines and are freely accelerated to high energies. Due to curvature emission, they emit gamma-rays, which are absorbed by the magnetic field and create electron-positron pairs, a process known as "pair-production". These pairs increase the particle density, which is amplified by the fact that each gamma-ray can lead to the creation of several pairs.

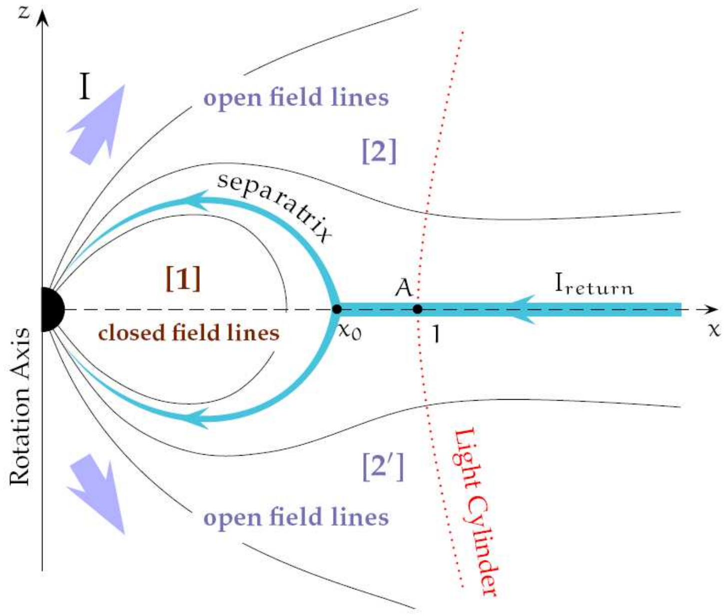


5. Towards a Dynamical Model of Pulsar Electrodynamics

30 years after Goldreich and Julian first proposed their model, the development of advanced computers made it possible to simulate the interaction of the plasma with the electromagnetic field and be therefore less dependent on highly simplifying analytical solutions. The presented model is based on simulations by Spitkovsky et al. in 2004 and summarizes more recent research in pulsar electrodynamics.

The spindown of a magnetized sphere already provides the two most important physical processes in pulsars assumed today: A rotating magnetic field, which induced an electric field and the sweepback of the magnetic field. Both processes combined result in an outwards Poynting flux. The special cases of the plasma-filled and the vacuum-case have different reasons for the electric field and the sweepback. In vacuum, the electric field is caused by induction and the sweepback is due to a displacement current. For the plasma-filled case, the electric field occurs because of net charge density and the sweepback is driven by poloidal currents (unlike in the vacuum case, the presence of plasma leads to spindown, even for aligned rotators).

The central question is, how these currents are set up, how they circulate and close. Further, it is likely that the details should be vitally dependent on the plasma supply.

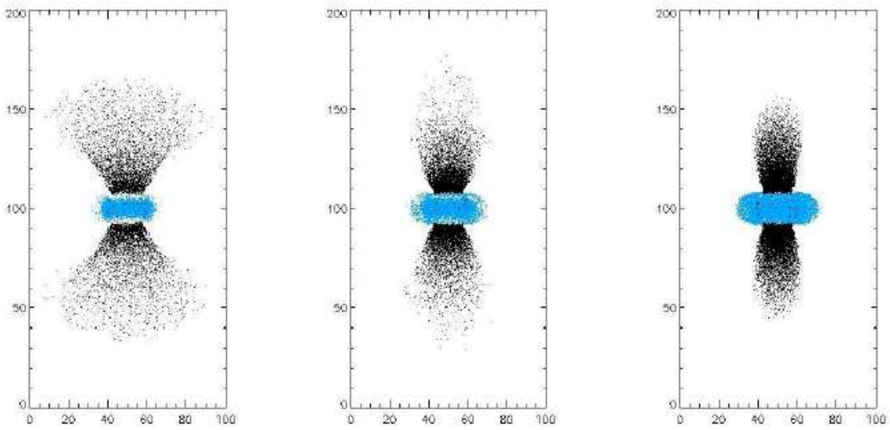


Rotating conductors in magnetic fields lead to Lorentz forces: These separate the different charges inside the conductor, which leads to potential differences on the surface. Electric fields outside the conductor can extract charges from the surface, which lead Goldreich and Julian (1969) to their charge-separated model, with a magnetosphere filled with charged particles extracted from the surface (however, it has been successively questioned, how realistic this model is).

Numerical simulations of the complex interactions of plasma with pulsar magnetospheres has brought more dynamic models, as they are not limited to quasi-static equilibria, which stay analytically solvable.

When a conducting sphere with a dipolar magnetic field is rotated, an electric field is inducted, which corresponds to a central monopolar charge plus quadrupolar surface charge.

This field attracts negative charges to the poles and positive charges to the equatorial region and has natural trapping regions. When the particle flow begins and the particles begin to fill the magnetosphere, they provide quadrupolar space charge which tends to cancel the electric field at the surface, which was the reason for the particle flow in the first place (a typical effect of induction). This reduces the surface charge and the particle injection and leads to a quasi-steady state. In 2D-simulations it is shown, that in this state “domes” of negative charge exist at the poles and a positive toroidal region around the equator with an electric gap in between.



Inside these plasma regions, there are no accelerating forces, and the mean plasma-density is a bit below the Goldreich-Julian-charge-density. The total size of the “domes” extends to several neutron star radii, and the magnetosphere does not lead to longitudinal currents, magnetic sweepback or spindown.

However, in 3D this quasi-stable state becomes unstable. Some field lines pass through the positively charged torus as well as through the vacuum gap. As these field lines are not equipotentials, plasma along them does not corotate with the star – a differential rotation that leads to an instability known as “diocotron instability”. It is comparable to the “Kelvin-Helmholtz-instability” in normal fluiddynamics. The two sheets of charge, with flow past each other form two surface waves which propagate in opposite directions and flow over each other.

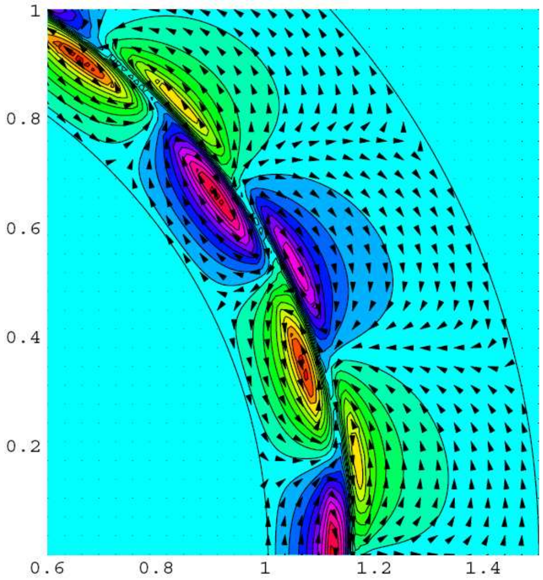


FIG 4. 6 A simulation of the diocotron instability at the outer rim of the pulsar magnetosphere. Potential perturbation is shown by coloured fields, the corresponding perturbed electric field is represented by arrows.

Inside the instability, the charge density perturbations grow by transporting charge across the field lines. This is due to the Lorentz force and the poloidal shape of the magnetic field (this was also observed in simulations). The instability works against the differential rotation by moving charge density. In simulations it could be seen that the positively charged torus grew with time and approached GJ-density.

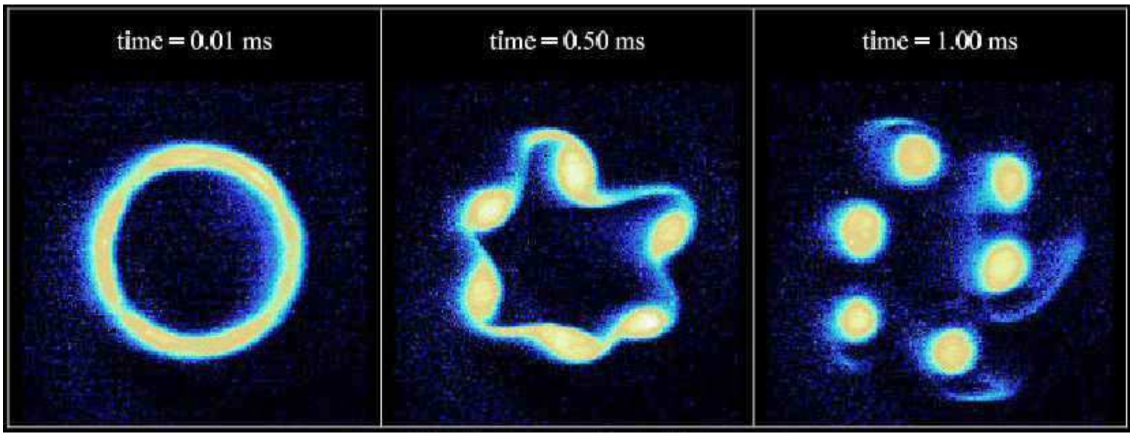
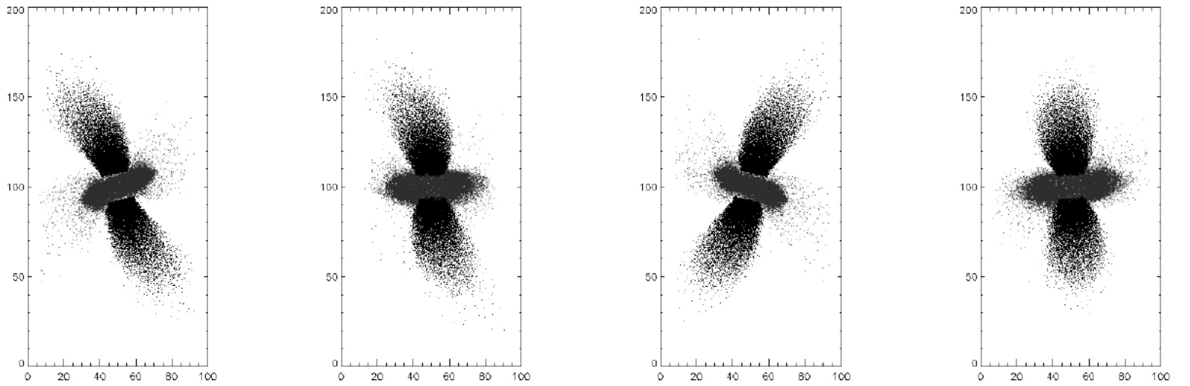


FIG 4. 7 This experiment with a plasma ring shows the formation of diocotron instabilities.

However, in 3D simulations the static "dome-like" electrospheres became unstable and the magnetospheres became active again: In the GJ-model a corotating closed field line region is crucial, as rotating charged particles in it provide the current necessary to modify and open the poloidal field lines. The domes expand, because the radial transport of particles from the equator changes the charge on the star, and the domes therefore try to compensate. Present simulations could not provide yet the limit when the instability turns from mainly electrostatic to electromagnetic. At this limit, domes and disc would expand outwards to the light cylinder. One hypothesis is that the diocotron instability, together with a development of transient accelerating regions, leads to a decoupling of particles from the magnetic field, which change the magnetosphere geometry, leading to a sweep-back and a recoupling to the field lines.



Another possibility is, that the magnetic inclination is vital for the “jump-start” of a pulsar. Pair-production as an emission mechanism is compatible with this model, but for a detailed, full understanding of pulsar physics advanced simulations and a deeper understanding of the underlying physics of magnetized plasma in magnetic field will be necessary.

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