

# Planetary Magnetic Fields

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## Introduction

Magnetic fields are a complex and important phenomenon in the solar system (and, indeed, beyond). Their causes are complex and, in some cases, controversial or mysterious, they have a variety of effects on their surroundings, and they have become both a critical target of the exploration and a critical tool for the exploration of solar system bodies. Some of the recent surprises in solar system exploration have been directly attributable to magnetic fields and their interaction with their environment.

In this paper I will briefly review some of the important steps in our discovery of magnetic fields, some of their key properties, models of how they are formed and maintained, and some of the general effects magnetic fields have in the vicinity of a planetary body. Finally, I will review the planets and some other selected bodies in our solar system, and comment on the key points of their magnetic properties.

## History of Discovery

For this study, it is sufficient to define magnetism as one aspect of the electromagnetic force, which attracts or repels under certain conditions, and is related to the movement of electrical charges. Plotting the force around a magnetized object reveals *field lines*, where the attractive forces are contoured into characteristic shapes around the object.

Most of the early discoveries into the nature of planetary magnetic fields were made by studying the most accessible magnetized object: the Earth, or the most powerful: the Sun. Except where otherwise noted, the following synopsis is based on Stern (2004).

It has been known since ancient times that magnetized objects responded to some kind of force inherent in the Earth. Chinese legends suggest compasses were used in 2634 BC, and the first *recorded* use is found in a Chinese text published at the end of the 11<sup>th</sup> century (Dyal 1992). Attempts to explain the workings of the phenomenon began with William Gilbert in 1600. Analysing multiple compass readings, including northward orientation and downward dip, he developed a model of a magnetized Earth. He believed that the Earth's rotation and its magnetism had a common cause, suggesting the Earth rotated *because* it was magnetic.

Amateur astronomer Heinrich Schwabe, searching in 1826-1843 for the proposed planet Vulcan inside Mercury's orbit, discovered the 11-year sunspot cycle and noted that geomagnetic storms corresponded to sunspot maximums (Columbia 2005). Fifty years later, two parallel discoveries tied this phenomenon to the Earth. In 1907 Carl Stormer showed how energetic charged particles can be trapped in the field of a dipole or a magnetized sphere and, in 1908, Hale showed that sunspots were intensely magnetic by observing the Zeeman effect – the splitting of absorption lines in the spectrum of light under the influence of a strong magnetic field (Zeeman 1897) – in

the spectra of sunspots. In 1919 Joseph Larmor introduced the fluid dynamo model when he proposed that sunspots, and the Sun's magnetic field itself, were the result of a self-sustaining dynamo in the plasma interior (Larmor 1919).

250 years after Gilbert suggested magnetism caused rotation, Blackett (1947) proposed the opposite: that all rotating bodies are magnetic, but this could not explain the Earth's historical pole reversals. Finally, a decade later, Parker (1955) gave the fluid dynamo proposal that is essentially the model used today. This model has been refined and supported by intensive computer simulations, the most accurate of which to date is by Takahashi et al (2005).

Since these historical starts, further advances have come largely from in-situ measurements of magnetic fields through spacecraft exploration. This has become such a powerful investigative tool that appropriate instrumentation is almost always including on exploratory craft.

## Properties of Planetary Magnetic Fields

Magnetic fields in planets can be broadly divided into two categories: *remanent* fields and *intrinsic* fields, plus an intermediate form in which a field is induced by an external force.

A *remanent field* simply indicates that an object was once magnetized and still retains the magnetism, like a traditional bar magnet. A remanent field has three requirements: (1) A material capable of holding a magnetic field; (2) An initial force to cause the magnetization; and (3) A temperature sustained below the *Curie Point*: the temperature above which a given material loses its remanent magnetism (Beatty, Petersen et al. 1999). Remanent fields are stable, and are not a good model for a field whose polarity is seen to change.

An *intrinsic field* is an active phenomenon resulting from some property of the object. Most planetary magnetic fields are self-sustaining intrinsic fields generated by an internal dynamo, following the model first proposed by Parker (1955) and later modified to become Kinematic Dynamo Theory (Fortes 1997). This model requires that a planet have (1) A molten outer core of a conducting material; (2) convective motion within the molten core; and (3) an energy source to power the convective motion.

Given an initial "seed" magnetic field, convective motion causes the conducting fluid to move in the presence of the magnetic field. According to Maxwell, this motion generates electric currents in the fluid. Still according to Maxwell, the moving current in the turbulent fluid generates a Magnetic field, which amplifies or reinforces the original field. Any small ambient magnetic field is sufficient for the seed field. Although self-sustaining, this is not a perpetual motion machine, as the field is sustained only as long as the energy source is present to power the convection.

If a system with some of the conditions necessary for a dynamo is imbedded in a time-varying magnetic field (such as of a parent planet or the passing solar wind), the dynamo may still function, generating a field that is said to be *induced* by the ambient field. Akasofu (1982) demonstrated that the interaction of the solar wind and a planetary magnetosphere is equivalent to a dynamo, modulated by the changes in the plasma flow of the solar wind.

## Poles and Orientation

A simple dipole is a convenient model but magnetic theory does not restrict a magnet to having two poles. Most magnetic fields behave like a summed series of fields of varying complexity: a

dipole combined with a weaker field having 4 poles, a still weaker field having 8 poles, and so on (Fortes 1997). Some planets (e.g. the Earth and Saturn) are well modelled by a simple dipole, while others (e.g. Neptune and Uranus) have significant non-dipole components that must be taken into account.

Since the first planet studied closely – the Earth – has its dipole nearly aligned with its axis of rotation, it seems reasonable to assume that there is some reason this *should* be the case; and to ask why the dipole is not, in fact, *precisely* aligned with the rotation axis. It turns out the orientation of the dipole need not be related to the axis of rotation and that the angle between the two is more a function of the nature of the internal dynamo.

Dipole magnets also have “North” and “South” poles, and not all of the planets have the same pole pointing up or down. Their orientation is coincidental since they reverse periodically.

Magnetic fields behave as though they are anchored to the interior of the planet, and rotate at the speed at which the planet rotates.

### Field Strength

Appendix I (pg. 13) shows the strengths of planetary magnetic fields vary greatly. Vallée (1998) demonstrates that a planet’s dipole moment is often related to its angular momentum:

$$\begin{array}{ll} \text{Angular momentum} & A = 0.4\omega(\text{mass})r_{\text{surf}}^2 \text{ where } \omega = 2\pi \cdot \text{rotation}^{-1}; \text{ and} \\ \text{Dipole moment} & M_{\text{surf}}(\text{Gauss} \cdot \text{m}^3) \approx 4 \times 10^{-9} A^{0.83} \end{array}$$

This can easily be tested. In seeking a model for field strength, it seems prudent to consider only the planets with intrinsic dynamos, and also to ignore the two moons of Jupiter who have fields, since they are likely affected by their immersion in Jupiter’s intense field. Appendix II (page 13) shows the calculation of these figures and correlations with the dipole moment.

The given formula correlates well with dipole moment, and mass of the planet is clearly the most important factor, with radius<sup>2</sup> second. This is intuitive, since they would give an indication of the volume available for interior conducting fluid. The low correlation of rotation speed is also consistent with even very slow-rotating Mercury having an intrinsic field, and given that rotation speed has been found insignificant compared to other forces (Ness 1979).

Note that there is no physical justification for this relation, and it has been called a “magnetic Bode’s law”, implying it is just an empirical fit to the data.

### Effects Surrounding a Magnetized Planet

Planetary magnetic fields would be less interesting if the planets were suspended in a neutral vacuum. Interplanetary space, however, is neither neutral nor empty. It is filled with plasma infused with a moving and time-variable magnetic field. The plasma is the *solar wind* – a stream of energetic ions ejected from the Sun’s corona and streaming radially at a speed of 450 km/s. The magnetic field present in the Corona is carried by the out-flowing particles, so the solar wind is said to carry an *entrained* magnetic field. Although the solar wind is extremely tenuous, and thus collisions are rare, it still behaves much like a fluid, with magnetic forces replacing physical interaction as the main mechanism (Beatty, Petersen et al. 1999).

Tom Gold first coined the word *magnetosphere* for the region around a magnetized body where magnetic forces are a dominant factor in phenomena (Gold 1959). The diagram in Appendix III (pg 14) shows the basic structure of a typical magnetosphere.

Up to a certain distance from the planet on the upstream (sunward) side, the magnetic field strength of the planet is sufficient to deflect the solar wind. This distance depends on the planet’s field strength and on the solar wind pressure at that point.

This deflection is “unexpected” because the solar wind travels so fast that no information can travel upstream in a return wave to gently deflect the flow. Instead, the wind is slowed suddenly and violently, causing a shock wave, turbulence, and heating of the plasma (Russell 1987). The point where this occurs is called the *bow shock*. The boundary where the majority of the solar wind follows field lines around the planet is called the *magnetopause* (Russell 1972-a).

Inside the magnetopause, the magnetosphere is not a vacuum – some plasma exists in that region. There are two main sources for this magnetosphere plasma: some solar wind that leaks through the magnetopause, and some plasma that consists of ionosphere particles, energized by UV or magnetic forces sufficiently to escape the ionosphere. The rotating field also ionizes and strips particles from rings or satellites, adding them to the magnetosphere plasma.

Downstream, the solar wind continues to flow around the planet, gradually moving back in to fill the cavity, thus forming a long *magnetotail* pointing away from the sun. Magnetotails are often hundreds of planetary radii in length, and contain time-varying and turbulent patterns of plasma.

### Non-Magnetic Objects in the Solar Wind

Even non-magnetized objects have an electromagnetic interaction with the solar wind, and result in having a magnetosphere. An unprotected solid object such as the Moon encounters the solar wind directly on the surface, and this creates a bow shock and tail. An object with no magnetic field but with an atmosphere, such as Venus, can have a complete magnetosphere because the ionosphere of the planet interacts with the solar wind and behaves like a magnetic field. With this more general definition of a magnetosphere, we can say that every object encountered to date has a magnetosphere, whether it has an intrinsic magnetic field or not (Russell 1991).

### Survey of Solar System

Appendix I on page 13 summarizes some basic properties for the planets and selected satellites in the solar system. Several basic groupings are evident from this table. For example, we can group objects by whether they have a magnetic field and of what type:

Intrinsic	Induced	Remanent	None, or Unknown
Sun	Europa	Moon	Venus
Io		Mars	Most other satellites
Mercury			Pluto, etc.
Ganymede			
Earth			
Saturn			
Jupiter			
Uranus			
Neptune			

Clearly the two extremes are the most common. Objects either have a self-sustaining dynamo or no field at all. The remanent and induced cases are rare exceptions.

The following sections list each of the planets and selected satellites and comment on their magnetic properties. The Sun and the Earth are described first as a basis for comparison.

## Sun

The Sun has an intense magnetic field that is highly variable and complex in shape. A simple dipole model does not fit the measured field well. The Sun's field mechanism is a self-sustaining fluid dynamo based on internal rotation. A circuit rotating as a solid body does not produce a dynamo – a differential across parts of the circuit is necessary (Stern 2004). Fortunately, all of the Sun does not rotate as a solid body. The outer third rotates differentially, while the inner two-thirds rotate as a solid body. The boundary between radiative and convective zones, where the differently rotating fluid masses shear past one another, is the site of the dynamo (Beatty, Petersen et al. 1999).

Since magnetic field lines tend to be “anchored” to the interior dynamo where they are produced, rotation complicates the field – the field lines become wrapped around the sun, tangled and kinked, and even protrude from the surface at points. sunspots are the visual result of these tangled field lines protruding through the surface. sunspots almost always occur in pairs, with different magnetic polarity – one where a field line protrudes from the surface, and another where the same line re-enters the sun. The intense magnetic field around the field line pushes charged plasma away, creating an area of lower temperature, visible to us as a darker patch.

The 11- and 22- year sunspot cycles are also a result of this field tangling. As fields wrap around the sun, they wind tighter and tighter, more so near the equator. The average latitude of sunspots moves toward the equator with the tightening fields. Eventually, the field lines become so tightly packed that they reconnect and cancel, the field reverses, and they begin to unwind. The process takes approximately 22 years. (Freedman and Kaufmann III 2002)

The magnetic field also explains the surprisingly high temperature in the Sun's corona, where the temperature jumps from 5000-10000K to 1,000,000K with no visible cause. Magnetograms show intense arches of magnetic field lines lacing 10,000s of km through the corona. When two such arches pass close to one another, they interact and release the energy that heats the corona to such high temperatures. This explains why coronal emissions are particularly intense, especially in X-Rays, over areas of heavy sunspot activity.

Finally, the magnetic field imprints itself on the out-flowing the solar wind, becoming the interplanetary magnetic field (IMF). Although the solar wind flows straight out from the sun, the sun is rotating, so it twists the anchored magnetic field into a spiral shape. Far from the Sun the IMF can impinge on a planet almost at right angles to the sun-planet line because of this spiral twist (Bieber 1992) and (Parker 1958).

## The Earth

The Earth has an intrinsic magnetic field modelled by a dipole tilted approximately  $12^\circ$  from the spin axis. The dipole moment is  $7.8 \times 10^{15} \text{ Tm}^3$  and the surface field is about  $1/3 \text{ G}$ , or  $3.11 \times 10^{-5} \text{ T}$ .<sup>1</sup> The dipole component is decreasing in strength by about 5% per century, but other

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<sup>1</sup> Magnetic force is generally measured in Gauss or Tesla, where  $1\text{T} = 10000\text{G}$ . Small quantities may be quoted in nT: nanoTesla, or  $10^{-9}$  Tesla.

components are getting stronger. At present, the quadrupole component is only about 0.14x the dipole component (Russell 1991). The north magnetic pole is located in Northern Canada, and is drifting north at an average rate of about 10km per year, as shown in Appendix IV (pg 15). It is not known whether the current drifting of the pole and weakening of the field are related to another phenomenon, the periodic reversal of the polarity of the Earth's magnetic field.

The field reversal was discovered along with evidence of continental drift. In deep-sea chasms, where new sea floor emerges from crustal fissures and then separates, the spread-out sea bottom on either side of a fissure represents a sample of crust stretching back millions of years. In the early 1960s, it was noted that the magnetic field frozen into this solidified magma was laid out in strips of opposite polarity, parallel with the fissure. These strips represent the terrestrial magnetic field at the time the magma emerged and solidified.

According to this record, the Earth's magnetic dipole has reversed polarity many times (Morley 1986). The frequency of reversal also varies with time. 60 million years ago the field reversed every 500,000 years on average, but for the last 10 million years reversals have been every 150,000 years on average (Russell and Luhmann 1997-c), except that the last reversal was 750,000 years ago. Appendix IV (pg 15) shows a timeline of reversals.

Reversals appear to take several thousand years and, during a reversal, the magnetic field does not vanish, nor does it pass through a "zero" point where there is no field. Instead, the dipole component shrinks to near zero but is replaced by higher order components. So a reversal is a period of more complex magnetic fields, possibly with multiple poles, after which a polarity-reversed dipole re-emerges.

The cause of field reversal is not known, but it is widely believed to be a natural result of the function of the fluid dynamo. Several recent computer simulations of the fluid dynamo have successfully shown a field reversal, even when they were not designed to do so. (Glatzmaier and Roberts undated, circa 2004). A minority proposes that an external event such as a major meteorite impact may be the catalyst for field reversals (Muller 2002).

The Earth's magnetic field cannot be remanent, since the interior is far hotter than the Curie point (770°C) for the metal core, and since remanent fields would not exhibit pole reversals. Instead, the field is the result of a fluid dynamo in the turbulent liquid metal outer core. The energy source to power the dynamo is internal heat, fed by a combination of core solidifying, precipitation of solids, and possibly radioactive decay (Stern 2004).

The Earth's magnetosphere extends about 10 radii on the dayside, and the magnetotail is thousands of radii long on the outer side (Baker 1992). Close to the planet, 25,000-40,000 km out, the *plasmasphere* is an area of trapped ions captured from the ionosphere, which rotates with the planet and carries the currents that generate geomagnetic storms. Further out, the magnetosphere contains mainly solar wind ions that leaked through the magnetopause.

Overlapping these two regions are the Van Allen Belts, named after James Van Allen, who insisted that charged particle detectors be included in the 1958 Explorer 1 and 3 satellites. Charged particles in the magnetosphere are trapped by the magnetic field in two large torus-shaped rings. The inner belt, at an altitude of 2000-5000 km, contains mostly protons resulting from the interaction of cosmic rays with the atmosphere. The outer, from 13,000-19,000 km, is mainly electrons, and carries a current (Freedman and Kaufmann III 2002).

The most visible and spectacular effects in the magnetosphere are *Geomagnetic Storms* and *Aurorae*. Geomagnetic Storms are major disturbances in the magnetosphere, resulting from a build up of energized particles in the magnetotail. Being fed and modulated by the solar wind, their frequency and intensity is also correlated with the sunspot cycle. Energetic particles, diverted around the magnetopause, build up in the magnetotail, which increases in size and current strength, and moves closer to the Earth. After a threshold is reached, often triggered by a shock wave in the solar wind, the energy is released suddenly. Some is ejected outward, and some toward the Earth, causing a variety of effects. Auroras, which can happen outside geomagnetic storms but are more intense during storms, result when released energy follows the magnetic field lines inward and excites atoms in the atmosphere. Auroral colours are characteristic of excited Oxygen (green and red) and Nitrogen (blue).

## **Mercury**

In 1974-5 Mariner 10 performed magnetic surveys of Mercury and discovered a magnetic field and magnetosphere. The field is much weaker than the Earth's, with a moment of only  $3 \times 10^{12} \text{ Tm}^3$ , and a surface field strength of about 250nT. The field is a dipole, tilted  $14^\circ$ .

It was originally thought that Mercury lacked the liquid core needed to produce a dynamo, but new data, from very precise measurement of libration, is consistent with the planet still having a thin layer of molten material, and this fits the dynamo model well (Kerr 2005).

The combination of weak magnetic field and strong solar wind from proximity to the Sun results in Mercury having a very small magnetosphere, so the planet occupies much more of its magnetosphere than does any other planet. Solar wind pressure can compress the upstream side of the magnetosphere right to the surface, exposing it directly to the solar wind (Criston 1992).

## **Venus**

After multiple exploratory craft visits to Venus, no intrinsic field has been detected, while some probes have detected a bow shock and other properties of a magnetosphere, believed to be induced from interaction of the solar wind with the atmosphere and ionosphere.

Venus far exceeds the Curie temperature, so no remanent field is possible. Although it probably has a molten interior, it is *too* hot to have the temperature gradients necessary for a dynamo. A dynamo may start in the future if the interior cools sufficiently to be turbulent (Fortes 1997).

Venus has a conducting ionosphere that acts as an obstacle to the solar wind much as a magnetic field would. The solar wind interacts with the ionosphere to produce a magnetosphere with the usual features, such as a boundary (called an *ionopause* instead of a magnetopause) and a tail.

## **Moon**

No intrinsic field has been discovered on the Moon, nor any sign of a molten core. However, there are significant remanent fields in the crust. Lin & Mitchell (1998) call "the discovery of strong stable components of natural remanent magnetism . . . major surprises of the Apollo program". It appears the Moon had a field similar to the Earth's during the period from 3.6 to 3.8 billion years ago, but its cause, and why it vanished, is unknown (Ness 1979).

## **Mars**

Early exploratory missions to Mars found conflicting information. Solar Wind was being held off from the planet, but the tenuous atmosphere was not sufficient to explain this. Further exploration found that, although there is no evidence of an intrinsic magnetic field, Mars does have a strong remanent field. This is also consistent with fields detected in meteorites of Martian origin.

To have a remanent field now, Mars must have had a strong field in the past. This is now considered certain, particularly since ESA's Global Surveyor found magnetic striping on the surface similar to the sea-floor striping on the Earth (ESA 2005). Mars apparently had an active dynamo for the first few hundred million years, but it stopped working about 4 billion years ago for unknown reasons (Acuña, Connerney et al. 1999). To achieve the strength of the current remanent field, the original field was probably quite strong, although Scott & Fuller (2003) have proposed that the chemical production of concentrated magnetite may have permitted a strong remnant with only normal original field strengths.

Mars has a magnetosphere and experiences aurora. However, these are of a type very different from the other planets: not polar but, rather, highly concentrated local effects controlled by magnetic anomalies in the crust (Bertaux, Leblanc et al. 2005).

## **Jupiter**

Jupiter's magnetic field was discovered by accident, as a result of its radio emissions, in 1955, when researchers found a moving radio source at 22.2 MHz which they were eventually able to correlate with the position of Jupiter (Franklin 1959). Pioneer 10 and 11 investigated further and confirmed the presence of powerful radiation fields and of the transmission of RF energy in 2 wavelength bands: 10 metres, associated with electrical discharges in the ionosphere related to the position of the moon Io; and 1-3 metres from a toroidal region not aligned with the planet's equator (Drake 1985).

Jupiter's field is modelled by a dipole tilted  $9.6^\circ$  to the axis of rotation. The dipole moment,  $1.6 \times 10^{20} \text{ Tm}^3$ , is 20,000 times more powerful than the Earth's, and the surface field is 10 times more powerful. The field is richer in harmonics than the terrestrial field, with a quadrupole contribution of 0.22 of the dipole. This seems to be a rule: the Jovian planets have more complex fields because the dynamo source is closer to the surface of the planet (Russell and Luhmann 1997-d). The magnetic field co-rotates with the planet, with a period of 9 hours 56 minutes.

Jupiter's magnetic field is generated by a fluid dynamo, but not based on molten metal. Instead, the conducting fluid is Hydrogen compressed to more than 1.4 million times the atmospheric pressure of the Earth, a point at which it develops metallic properties and becomes a conductor – an effect which has now been reproduced in laboratories (Weir, Mitchell et al. 1996). Convective currents in this fluid provide the turbulence needed for the dynamo, and the energy source is largely heat released by precipitation and cooling of internal materials.

With the powerful magnetic field and the weak solar wind pressure at its great distance from the sun, the Jovian magnetosphere is enormous. Considered as an object, it is by far the largest object in the solar system, considerably larger than the Sun. If it were visible from the Earth, it would appear many times larger than the full moon. It is extremely variable in size, expanding and contracting by a factor of 2 with changes in the solar wind. The upstream bow shock is generally



50 to 100 planetary radii from the planet. Downstream, the magnetotail extends more than 5 AU – beyond the orbit of Saturn (Russell and Luhmann 1997-d).

At least 7 of Jupiter's satellites, including all 4 of the Galilean satellites, are contained inside the magnetosphere, and their surfaces are bombarded by energetic particles, eroding them and altering their chemistry (AstroEncyc 2002).

The magnetosphere contains a great deal of highly energetic plasma. The co-rotating magnetic field sweeps particles off moons and from their atmospheres, and Io's volcanic eruptions contribute more material. This material is ionized by the currents flowing in the magnetosphere and then accelerated by the rotating field to high speed, pushing it out into a disk shape around the equator. This highly charged and conductive plane is known as the *plasma sheet*. This charged environment produces many effects, including energetic aurora and erosion of material from Jupiter's ring. The most spectacular effect, interaction with the moon Io, is described below.

A Cassini flyby in 2002, combined with simultaneous observations from Galileo and two earth-orbiting telescopes, confirmed that the Jovian system is highly sensitive to changes in the solar wind. Direct measurements showed aurora and radio emissions were modulated by shock waves travelling through the solar wind (Hill 2002).

### **Galilean Moons**

The 4 Galilean moons of Jupiter deserve special mention, since they are in a unique environment, immersed in the Jovian magnetosphere.

#### ***Io***

Two aspects of Io are interesting from a magnetic perspective: its own magnetic field, and its interaction with Jupiter.

Io's magnetic field was discovered by spacecraft, beginning with the Voyagers, who first detected a drop of 695 nT in the level of the ambient Jovian magnetic field, best explained by a second dipole overlaid onto the Jovian field (Showman and Malhotra 1999). There was initial controversy over whether an intrinsic field was required to explain these observations (Frank, Paterson et al. 1996) but it is now generally accepted that Io has an intrinsic field generated by a dynamo, with a dipole moment of about  $8 \times 10^{12} \text{ Tm}^3$  and a surface strength of 1200 nT.

The dynamo mechanism is similar to the Earth's, based on turbulent flow in an internal layer of liquid magma rich in iron and magnesium. The heat source for the dynamo is tidal heating resulting from Io's orbital resonances with Europa and Ganymede, and from the magnetically induced current flow with Jupiter described below (NASA 2000).

With Jupiter's rapidly rotating magnetic field, the Io-Jupiter system also forms a dynamo, causing 400,000 volts of potential to form across the moon, and 5 million amps of current to flow through it. There is also a powerful current flow between Io and Jupiter, through a line of plasma known as the *flux tube*. It is this intense current flow, essentially an electric arc orbiting Jupiter under Io, that causes the radio emissions detected by Franklin and Burke in 1955.

To further complicate the system, Io is intensely volcanic, ejecting tons of material – largely sodium and potassium – into its atmosphere every second. More material is sputtered off the surface of Io by collisions with orbiting magnetospheric ions. Much of this is ionized by the

intense electrical and magnetic activity. These ions are then captured by Jupiter's rotating magnetic field and accelerated to become a torus of energetic ions aligned with Jupiter's magnetic equator. These spiralling ions are the source of the synchrotron radiation later detected.

It adds about 1000 kg of material per second to the torus. Since the torus is stable in size, some other process must be removing material. Torus material is orbiting faster than its escape velocity, and is held in place by magnetic forces on the ions, not by gravity. When an ion recombines with an electron to become neutral, magnetism loses its effect, and the molecule is rapidly ejected from the system, forming an extended "neutral sodium cloud" so large that it is visible from the Earth (Pontius 2000).

### ***Europa***

The Galileo spacecraft detected evidence of a magnetic field at Europa in 1997, by observing "substantial departures from the Jovian ambient magnetic field" (Kivelson, Khurana et al. 1997-a). The field varies with Europa's position in Jupiter's magnetosphere, which an intrinsic field would not do, so it is now agreed that the best fit to the observations is a magnetic field in a subsurface conducting liquid layer induced and modulated by Jupiter's ambient rotating magnetic field (Kivelson, Khurana et al. 2000). This weak field has a dipole moment of about  $7 \times 10^{11} \text{ Tm}^3$  and a surface strength of about 240 nT. The dynamo fluid is most likely a subsurface ocean of salty water.

### ***Ganymede***

When the Galileo craft discovered evidence that Ganymede has a self-sustaining intrinsic field, it was the first moon known to have that property. Galileo detected strong disturbances in the Jovian field around Ganymede, and Kivelson (1997-b) concluded only an intrinsic field could produce the measured effects.

Ganymede's field is twice as strong as Mercury's, 750nT at the equator. The dipole moment is  $1.4 \times 10^{13} \text{ Tm}^3$ , tilted 10 degrees to the spin axis. The field's mechanism is still somewhat of a mystery. There may be a subsurface layer of salty water, but this would not be sufficient to explain the field, so there may also be a liquid or partially liquid inner core of iron or iron sulphide (Showman and Malhotra 1999). Jupiter's ambient field was likely the dynamo seed (Sarson, Jones et al. 1997).

Ganymede has its own simple magnetosphere, and the Hubble telescope has confirmed that it experiences its own aurora as well.

### ***Callisto***

Galileo detected no evidence of a magnetosphere at Callisto, or of an intrinsic magnetic field. However, there is some disturbance of Jupiter's ambient magnetic field, which is believed to be from an induced field in an internal conductor. In fact, the presence of this field is used to argue for the existence of a subsurface salty ocean (Khurana, Kivelson et al. 1998). The field is very weak, with a surface strength no more than 30 nT.

## Saturn

Saturn has a magnetosphere and an intrinsic magnetic field supported by a self-sustaining dynamo similar to Jupiter's, although much smaller and weaker. The dipole moment,  $4.7 \times 10^{18} \text{ Tm}^3$  is about 600 times the Earth's, but the surface field strength is about the same.

Unlike any other planet, the tilt of Saturn's dipole is near zero. For some time, it was believed to be *equal* to zero and, while this seems elegant at first, it is actually quite problematic since it has been proven that a fluid dynamo cannot be perfectly symmetric around its axis (Cowling 1934). Now models have been found that allow the tilt to be as little as  $0.5^\circ$ , and it is estimated at  $0.7^\circ$ . The field is also very simple, almost a pure dipole, with the quadrupole contribution only 0.07x the dipole (compared to 0.14x for the Earth).

Saturn's dynamo fluid is liquid metallic hydrogen, like Jupiter, but in a smaller quantity. The dynamo's power source is heat released from the condensation of Helium, and gravitational energy released as heavier elements sink into the core (Russell and Luhmann 1997-a).

The magnetosphere is about 10-20% the size of Jupiter's but similar in structure. However there is less interior plasma or synchrotron radiation because it lacks a prolific source like Io, and because the rings absorb the majority of ions and electrons. There is a torus of  $\text{H}^+$  and  $\text{O}^+$  ions, probably from water ice sputtered off Dione and Tethys (NASA 2005).

Dark, radial projections, called "Spokes", have been observed in some of the rings, and it is believed these are magnetically induced, since they orbit at the same speed as the planet's magnetic field. Horanyi (1996) has further proposed they are an artefact of the interaction of ring material with a "dust-rich plasma" that would have the property of responding to both magnetic and gravitational forces, through being based on more massive particles.

Finally, the current Cassini mission has detected an unusual phenomenon. Km-length radiation, modulated by the rotating magnetic field, is showing a period 6 minutes longer than it did when measured during earlier visits 20-30 years ago. Since the rotating field is anchored to the planet, this seems to suggest the rotation of the planet is slowing down at a rather rapid rate. However, many such as Sanchez-Lavega (2005) point out that it is difficult to believe the planet is slowing down; conservation of momentum would require other changes, which are not observed. It is more likely that some other part of the system is more complex than originally thought.

## Uranus

Uranus immediately stands out among the planets since its axis of rotation is tilted  $98^\circ$ , sometimes with the axis pointing nearly directly toward the Sun, sometimes pointing nearly  $90^\circ$  away but across the ecliptic. The magnetic field also has a large ( $59^\circ$ ) tilt to the axis of rotation, and is offset significantly (about 0.3 radii) from the centre of the planet, and thus the surface field varies greatly with location. The dipole moment,  $3.9 \times 10^{17} \text{ Tm}^3$ , is about 50 times the Earth's. A dipole is not, in fact, an adequate model and the quadrupole contribution is 0.7; in other words, there is a 4-pole field almost as strong as the dipole field.

Uranus' magnetic field is intrinsic and dynamo-generated. The dynamo fluid is a relatively thin shell of highly compressed water with ammonia and other impurities. Laboratory experiments have shown that water under these conditions will conduct well enough to serve as the fluid for a dynamo (Celliers, Collins et al. 2004). Although it was originally thought that the large tilt of the

dipole must be due to some external influence, simulations have shown that large tilts are a natural result of dynamos using thin layers of conducting fluids (Stanley and Bloxham 2004).

Since the magnetic field is oriented closer to a right angle than parallel to the spin axis, the magnetic field lines are unusual. As they are swept back from the planet by the solar wind, the planet's rotation winds them into a corkscrew shape. Interaction will also change dramatically as the planet orbits the sun, changing the orientation of the spin axis to the sun (AstroEncyc 2002).

Surprisingly, the basic structure of the magnetosphere is *not* unusual. Although the spin axis is highly tilted, the high tilt of the dipole axis "undoes" this, and leaves the dipole oriented roughly perpendicular to the ecliptic, as it is for all the other planets. As a result, while the magnetic field is very unusual, the magnetosphere is very Earth-like (Russell and Luhmann 1997-h). It experiences magnetic storms, which produce planetary aurora, in much the same way as at the Earth, only much weaker because of the reduced density of the solar wind at that distance.

## Neptune

Neptune's magnetic environment is similar to Uranus' in some ways. While the planet's orbital axis is tilted only 30°, the magnetic field dipole axis is tilted another 47°. This leaves it substantially inclined to the planet-sun line. The dipole is also offset from the centre of the planet by 0.55 radii. Surface field strength varies by an order of magnitude around the planet because of this offset, while the dipole moment of  $2.2 \times 10^{17} \text{ Tm}^3$  is 27 times the Earth's. The field is highly complex and the quadrupole component is actually as large as the dipole component, making Neptune the least dipole-like planet in the solar system (Russell and Luhmann 1997-g).

Like Uranus, Neptune uses a thin layer of highly compressed water as the dynamo fluid. As already mentioned, the extreme tilt of the magnetic axis is likely a result of the geometry of this dynamo. Because of the magnetic tilt, and rotation tilt, the angle between the solar wind and the dipole axis changes dramatically twice each Neptunian day, causing complex and rapidly varying changes in the structure of the field lines and the magnetosphere.

## Pluto

Pluto, Charon, etc., have not been visited closely enough for magnetic measurements. However, it is improbable they will have magnetic fields, either intrinsic or remanent, since they are too cold for any known form of dynamo to operate.

## Conclusion

Planetary magnetic fields are a deep and complex field of study, with an interesting relationship with exploration. For remote objects, on-site exploration is necessary to gather information for magnetic study and, in return, magnetic information is a very powerful tool for making deductions about the interior structure of a planet and about its interaction with its immediate environment.

Planets' environments are made more interesting by the presence of magnetic fields and by the fact that interplanetary space is, in fact, rich with charged particles from the Sun, and an entrained magnetic field, that can interact with planetary magnetic fields in dynamic and energetic ways.

## Appendix I: Planetary Field Data

This table summarizes relevant information for the planets and certain other selected objects in the solar system. Consolidated from various sources, including (Beatty, Petersen et al. 1999), (Bagenal 1992), (Fortes 1997), and (Russell 1991).

Planet / Object	Distance from Sun (AU)	Radius (km)	Mass (kg)	Rotation (Earth Days)	Dipole Moment (Tm <sup>3</sup> )	Type	4-Pole Fraction	Tilt of Dipole	Which End Up?
Sun	0.0	695,510	1.99E+30	27.00	Variable	Dynamo	Varies	Varies	Alternates
Mercury	0.4	2,440	3.30E+23	58.65	3.00E+12	Dynamo		14	S
Venus		6,052	4.87E+24	243.02	< 8e10				
Earth	1.0	6,378	5.98E+24	1.00	7.80E+15	Dynamo	0.14	11	S
Moon		1,737	7.36E+22	27.32	< 1.3e8	Remanent			
Mars		3,397	6.42E+23	1.03	~ 1e11	Remanent			
Jupiter	5.2	71,492	1.90E+27	0.41	1.60E+20	Dynamo	0.22	9.6	N
Io		1,821	8.93E+22	1.77	~ 8e12	Dynamo			
Europa		1,560	4.79E+22	3.55	~ 7e11	Induced			
Ganymede		2,634	1.48E+23	7.16	1.40E+13	Dynamo			
Callisto		2,400	1.08E+23	16.69					
Saturn	9.5	60,268	5.69E+26	0.44	4.72E+18	Dynamo	0.08	~ 0.7	N
Uranus	19.2	25,559	8.68E+25	0.72	3.83E+17	Dynamo	0.70	58.6	N
Neptune	30.1	24,766	1.03E+26	0.67	2.16E+17	Dynamo	1.00	47	N
Pluto	39.5	1,150	1.30E+22	6.39	?				

## Appendix II: Factors Affecting Dipole Moment

If we use the following figures:

	mass	radius	rotation	radius^2	moment w	ang-mom	est-DM	
Mercury	3.30E+23	2,440	27.00	5.95E+06	3.00E+12	0.232710567	1.83E+29	7.76E+15
Earth	5.98E+24	6,378	1.00	4.07E+07	7.80E+15	6.283185307	6.11E+32	6.53E+18
Jupiter	1.90E+27	71,492	0.41	5.11E+09	1.60E+20	15.32484221	5.95E+37	9.02E+22
Saturn	5.69E+26	60,268	0.44	3.63E+09	4.72E+18	14.27996661	1.18E+37	2.35E+22
Uranus	8.68E+25	25,559	0.72	6.53E+08	3.83E+17	8.72664626	1.98E+35	7.91E+20
Neptune	1.03E+26	24,766	0.67	6.13E+08	2.16E+17	9.377888518	2.37E+35	9.18E+20

we can calculate correlation of the standard figures for dipole moment to mass, radius<sup>2</sup>, rotation, and the estimated dipole moment using the formulae:

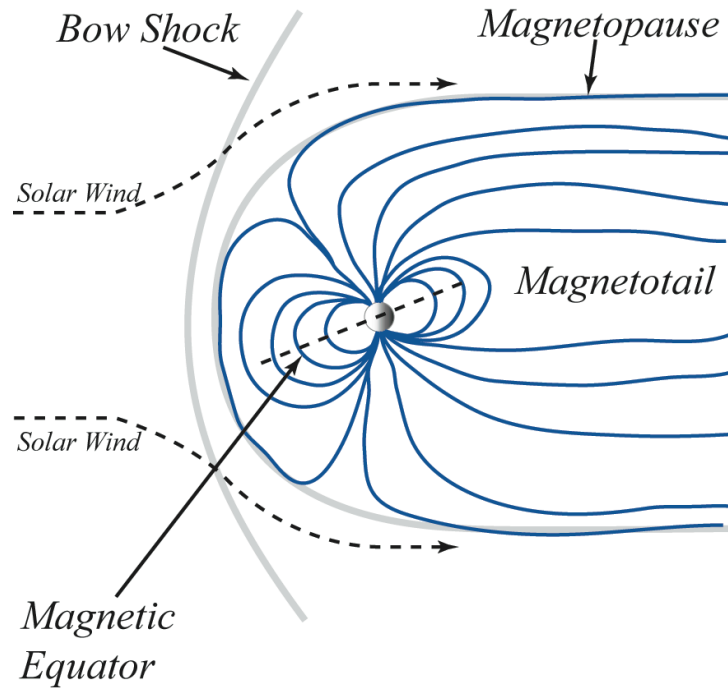
$$\text{Angular momentum } A = 0.4\omega(\text{mass})r_{\text{surf}}^2 \text{ where } \omega = 2\pi \cdot \text{rotation}^{-1}; \text{ and}$$

$$\text{Dipole moment } M_{\text{surf}}(\text{Gauss} \cdot \text{m}^3) \approx 4 \times 10^{-9} A^{0.83}$$

Correlation of moment to:

mass	0.966
radius^2	0.797
rotation	-0.219
est-DM	0.973

### Appendix III: Diagram of Magnetosphere



Simplification based on (Freedman and Kaufmann III 2002).

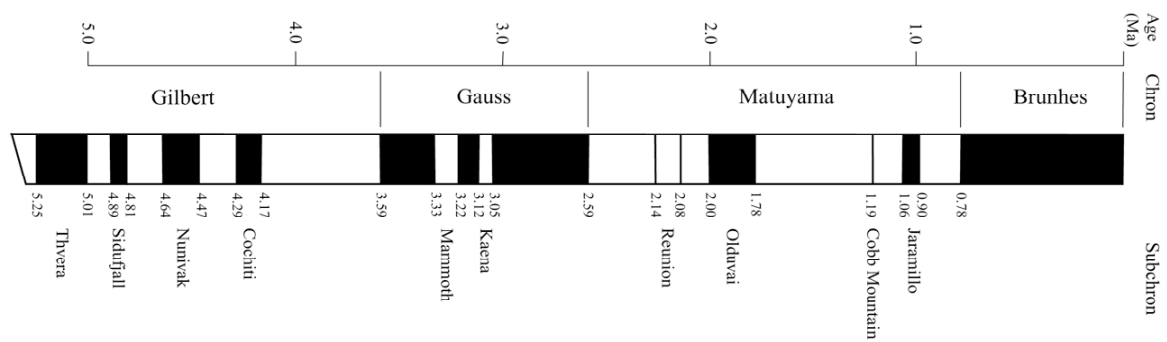
# Appendix IV: Pole Reversals and Drifting

## Drifting of North Magnetic Pole



From (Phillips undated).

## Historical Magnetic Field Reversals



This timeline of reversals is from (Wikipedia 2005-c):

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