A transpolar arc discovered on Saturn

4/29/15

There are still many mysteries surrounding the polar aurorae of the other planets in the solar system. They are a source of fascination for atmosphere specialists, and sometimes antagonistic hypotheses on their origins trigger heated debates amid lively controversies. On Earth, they mainly depend on the solar wind. A solar wind which, according to many theories, is incapable of penetrating the magnetosphere of gas giants such as Saturn or Jupiter. A team led by two researchers from the University of Liège could however make the scales tip the other way. Using the Cassini probe, it recently observed the formation of a transpolar arc on Saturn for the first time. A frequent phenomenon on Earth, but unsuspected on the giant planets, since it is very unlikely unless the planet's magnetic field captures particles from the solar wind.

Some travel to Norway, or to the great Canadian north to observe polar aurorae, and marvel at the incredible beauty of these displays of energy. However, these destinations are no longer exotic enough for planetologists specialising in atmospheric physics. Because space observatories, such as the Hubble Space Telescope or more recently the Cassini spacecraft, have allowed us to discover and observe the formation of aurorae on other planets in the solar system, i.e. Jupiter and Saturn. Theoretically, if a planet has a magnetic field and an atmosphere, aurorae can form in its atmosphere around the magnetic poles.

For Aikaterini Radioti and Denis Grodent, from the University of Liège's Laboratory for Planetary and Atmospheric Physics, Saturn, in particular, was once again the source of their attention, and was able to satisfy their curiosity. "Thanks to the UVIS spectograph on board Cassini", Aikaterini Radioti explains, "we observed the formation of a transpolar arc for the first time. It is a common occurrence on Earth, formed by repeated interactions between the magnetosphere and solar wind. But we didn't think it was possible on Saturn. Because its system has internal processes that play very important roles in the behaviour of the magnetosphere, which could prevent the formation of these arcs." The discovery could change what we know about Saturn. For instance, recognising that the solar wind strongly influences the deep regions of its magnetosphere, and finding similarities between these mechanisms and those observed on Earth, despite the huge differences that characterise these two planets.
Terrestrial aurorae, an external process

Before turning to the observations on Saturn, we should perhaps take a closer look at the phenomenon of polar aurorae. On Earth, they can be observed at both poles. There is the aurora borealis at the North Pole, and the aurora australis at the South Pole. But what we observe when we see these curtains of light in the sky is, in fact, nothing other than the signature of a mechanism that is happening much further away. It is the residue of an interaction between the Earth's magnetic field and the solar wind.

The Earth produces a magnetic field through a dynamo effect. With no external influence, this magnetic field might resemble a large apple, whose centre is the Earth. The area controlled by this field is what is known as the magnetosphere. But there is an external influence, and it is a considerable one: the Sun. Or rather, its winds, charged with particles, which take the sun's magnetic field with them. At the front, this solar wind compresses the Earth's magnetosphere. At the back, the terrestrial fields lines are very stretched out and form the magnetotail. This solar wind and the solar magnetic field it is transporting therefore encompass the Earth, surrounding it and taking its magnetosphere with it on its way. Once it has passed this obstacle, it continues on its course towards the far reaches of the solar system. Reconnection of the field lines occurs in the furthermost part of the magnetotail. During these reconnections, part of the solar wind is caught in the magnetosphere. The magnetic field is deformed and stretched, almost like an elastic, thus providing the system with energy. "If you stretch an elastic", Denis Grodent explains, "it will eventually snap back and hit your fingers. The energy
transferred from the elastic to you fingers will cause pain." The formation of polar aurorae is caused by the same transfer of energy. "The energy from the magnetic field is deformed and transferred to the magnetotail. This energy will heat up the particles there and excite them. They will travel along the Earth's magnetic field lines and up to the poles." When they come into contact with the atmosphere, they will excite its atoms and molecules (oxygen, hydrogen, nitrogen). These atoms, which can't remain in a state of excitement, will release energy by emitting photons, the elementary particles of light, and form aurorae. Therefore, the photons are only emitted in the atmosphere. And the aurorae only appear once the interaction between the different particles of the magnetotail and solar magnetic field lines has taken place. They are nothing more than the expression of a loss of energy. The signature of an interaction between ions, electrons and a deformed magnetic field, the sign of an exchange of energy happening outside the atmosphere, but which occurs because of a topological change in the magnetic field lines. "And an influx of energy is never free. You always have to pay for it. In this case, it's the Sun that pays the bill. The energy comes from the solar wind and it reappears in the ions."

Diagram of the Earth's magnetosphere
The area behind the illuminated face is called the tail.

An internal process for gas giants such as Jupiter

But this reconnection between the solar wind and the magnetic field in the magnetotail isn't the only cause of the appearance of aurorae. On some planets, these processes are internal, and don't depend on the Sun. This is the case of Jupiter. "The effect of the solar wind is very slight", explains Denis Grodent. "Jupiter's magnetic field is so enormous that it reinforces the magnetosphere and prevents reconnection between its magnetic field lines and those of the sun". However, the aurorae observed on Jupiter are of an unimaginable
intensity. The power they generate is measured in terawatts, and is much greater than anything we could ever produce on Earth with all our nuclear plants in operation. "To such an extent that it is mainly the aurorae that heat Jupiter's atmosphere", the two planetologists explain, "and by several hundred degrees. It's not the Sun." But the causal process of these auroral footprints is internal and linked to Jupiter's very fast rotation, which takes its magnetic field and the charged particles it contains with it. It is another of the magnetosphere's ingredients, also swept along by the planet's rotation, and unable to keep up with the pace, which upsets the physical mechanics of the process: plasma. In the case of Jupiter's magnetosphere, it is the volcanic moon Io that is the main source of plasma. Part of the molecules ejected during the continuous volcanic eruptions (Io is probably the most volcanic object in the solar system) are found in Io's atmosphere. These sulphur oxide molecules can be broken and ionised by the Sun's UV rays or by collisions with the ambient plasma and escape Io's gravitational force, thus filling Jupiter's magnetosphere with (plasma) ions and electrons.

"It doesn't turn fast enough, and according to the laws of electromagnetism, it isn't possible. Or, in any case, the system tends to make it return to the same rotation speed. Mechanisms are set up to attempt to remedy this corotation lag. That's the principle of corotation enforcement. A tiny part of Jupiter's rotational energy which is transferred to this plasma by electrical currents, which will generate a force capable of accelerating the movement of the plasma. It is these electrical currents that will travel along the magnetic field lines, excite the atmosphere and emit very high intensity rays."

Therefore, aurorae can be created by different processes, according to the planets' different properties. On Earth, they tend to be external, because the solar wind's particles pass more easily through the magnetosphere. On the gas giants, the solar wind will have less of an influence, and the aurorae are more likely to be the result of internal processes.

The controversy surrounding Saturn

Although Saturn is smaller than Jupiter, it is nonetheless a gas giant. Its characteristics remind us of those of its neighbour, both in terms of its composition and its behaviour. Just like its large companion, its magnetic field is far more powerful than the Earth's. The solar wind, given the greater distance separating the planet from the star, is less powerful, and its rotation speed is faster, since it only needs 10 hours to rotate on its axis. And above all, its magnetosphere also contains plasma, whose origin deserves a brief explanation. "Jupiter and Saturn are basically composed of hydrogen and helium in a neutral state", the researchers elaborate. "As regards Jupiter, the main source
of plasma is its moon Io, probably the most volcanic object in the solar system. As for Saturn, besides its rings, its Enceladus, which also has volcanic activity, or cryovolcanic to be more precise. There are massive geysers of water, that turn to ice. The liquid phase doesn't exist in space. When these eruptions take place, the matter ejected escapes the satellite's gravitational force (like for Io, Jupiter's volcanic moon) and is ionised by the Sun's ultraviolet rays, before being trapped by the planetary magnetic field in plasma form and accumulating in the magnetosphere. A process that applies to both Saturn and Jupiter.

The similarities shared by these two giants still lead a good number of magnetospheric physicists to believe that the origin of Saturn's aurorae is internal. "It's true that all the conditions for such a process to exist are present on Saturn. We even believe it's been observed in the ultraviolet, but not yet in the infrared. So it's not something very obvious. Consequently, there's a big question mark. Even though the two planets are quite similar, why does one present the auroral signature of a huge corotation lag, and not the other one?" A question that has led Aikaterini Radioti's team to examine a third possibility, whereby the origin of the aurorae shares characteristics particular to those of Earth and Jupiter. "A mixture between the cycles linked to the plasma and those dependent on reconnections with the magnetic field of the solar wind", the scientist continues. "This is the hypothesis we are putting forward, and which seems to us the most probable. At the same time, we haven't been studying the aurorae on these planets for very long. We're still at the discovery stage, and we're continuing to come up with a great many hypotheses, which haven't been verified. So the controversy continues." "Perhaps", Denis Grodent adds, "when we have the chance to study other giants like Uranus or Neptune, we shall understand physical systematics that will force us to rethink the mechanisms that we apply to Earth. For the moment, our paradigms work for Earth, but if they don't allow us to explain what is happening elsewhere, many things may be called into question. After all, physics must be applied in the same way everywhere."

**The transpolar arc on Saturn reinstates the solar winds**

On Jupiter, the Sun's magnetic field rebounds and bypasses the planet without penetrating the magnetosphere. Exactly in the same way as water from a river flows around a stone without altering it. However, for reconnection between the field lines to occur, the solar wind must penetrate the magnetosphere, like the water penetrating the porous surface of a stone. Why does the magnetic field slide off Jupiter and could it be trapped by Saturn? The answer probably lies in the intensity of the magnetic field, which is ten times greater than on its cumbersome neighbour, or in the fact that there is less plasma.

But Aikaterini Radioti and Denis Grodent are adament: reconnection processes are at the source of Saturn's aurorae. It is an interesting discover which allows them to confirm their intuition: the observation of the formation of a transpolar arc for the first time. A frequently observed phenomenon on Earth, but unexpected on Saturn. Remember that it is Saturn's internal process, linked to the force of its magnetic field and the presence of plasma, that prevents or, at the very least, greatly reduces, the possibility of an external process. Reconnection is therefore far rarer on Saturn than on Earth, where the magnetosphere is less effective at blocking the solar wind.
"In reality, there are two stages to the reconnection that takes place in the cycle of the external process. On the day side, i.e. the side lit by the Sun, the Earth's magnetic field lines, or those of Saturn, go in one direction, and the Sun's magnetic field in another direction. The lines closest to each other will open, and allow what is known as dayside reconnection. The Earth's magnetic field opens and its field lines connect with the Sun's. This is the Dungey cycle, named after the English physicist who discovered it. These field lines will then move back and, only once they are much further away, in the magnetotail of Saturn and reconnect on the nightside (green X)

(1) Dayside reconnection (Dungey cycle) : The magnetic field lines of Saturn open and connect with those of the Solar wind (blue X) 
(2) Nightside reconnection (Dungey cycle): These field lines will move further out in the magnetotail of Saturn and reconnect on the nightside (green X) 
(3) Nightside reconnection (Internal origin): The accumulation of plasma in the magnetosphere, which is produced by Saturn's rings and the cryo-volcanism of Enceladus, results in closed field lines to reconnect with each other on the nightside (red X).

"It's only a theory on the formation of arcs, but it's the most likely one as regards both Earth and Saturn. And yet, on Saturn, this process coexists with an internal process, which makes the Dungey cycle quite rare. Therefore, an accumulation of flux, which means several reconnections one after the other, must be an event that is even less frequently observed. We were really lucky to spot it. Before we observed it, we didn't even
think such an event could exist. In any case, this observation allows us to believe that if these arcs are indeed the effect of a reconnection linked to the solar wind on Earth, this is also the case on Saturn, and they are greater than we thought."

More and more observations

Hubble took the first images of aurorae on the gas giants. In 2004, the space probe Cassini, developed by NASA and ESA, went into orbit around Saturn leading to more precise observations, which fulfilled the expectations of research groups from a wide range of areas of study. In particular, it led to the discovery of the existence of geysers on Enceladus, the collection of a great deal of data on the composition of Saturn's rings, a better understanding of its atmosphere, its physical and climatic properties, but also its magnetic field, its magnetosphere, and the effect it could have on the formation of its aurorae.

But Cassini still has many wonders in store for us. "The mission was extended until the end of 2017", the researchers tell us enthusiastically. "Normally, Cassini turns around Saturn in the equatorial plane. But when the probe passes close to a satellite, we can use its swing-by to modify the orbit and tilt it towards the poles. And for the mission’s "Grand Finale", we expect to collect some amazing data. We'll have a near polar orbit. This course change will monopolise the probe's last resources. It will move closer to Saturn, enter its atmosphere and completely disintegrate there. But during the whole period leading up to its end, we will be able to observe the two poles from very close up, in detail, with a definition that is almost better than the one we have for Earth observations. We’ll have the day side and night side in the same frame, and we shall observe phenomena we aren't yet familiar with, which we probably still can't explain, that will allow us to confirm or abandon some of our hypotheses."

And the end of Cassini doesn't mean an end to the observation of the giant planets' aurorae. In 2016, Juno, one of NASA's new, and even more high-performance probes (with an instrument on board that the CSL (Liège Space Centre)helped to develop), will be put into orbit around Jupiter to carry on the work. These observations will simply be an initial area of research. Because the researchers are still at the discovery stage.

(1) Radioti, Aikaterini and al, Saturn’s elusive nightside polar arc, Geophysical Research Letters, Sept 2014