The Sun's crowning glory

May 11 2012, By Thomas Buhrke

Dark star surrounded by a circle of light: The outer gaseous layer of the Sun - the corona - can be seen when the new moon exactly covers its glaringly bright disk during a total eclipse. Credit: SPL - Agentur Focus

(Phys.org) -- Those who experience a total solar eclipse are overwhelmed as they look at the circle of light that surrounds our Sun. Laypeople may find it enchanting, but researchers have been racking their brains over it for decades. Why, they wonder, does this gaseous layer – the corona – have a temperature of several million degrees? Sami K. Solanki, Director at the Max Planck Institute for Solar System Research in Katlenburg-Lindau, and his team are tackling the problem with ingenious observation methods and computer simulations.

The institute sits amid tranquil meadows and fields, and a stroll through the entrance hall highlights the long tradition of solar system research. From the Helios space probes of the 1970s to Ulysses and Cluster to the modern solar observatories known as SOHO and STEREO – Max Planck researchers have been participating in all of these missions. Over the last ten years, probably the largest group of solar physicists in Europe has come together here. One of their main objects of study is the corona. “It is the interface between our star and its heliosphere, that is, the sphere of influence of the solar wind, in which our Earth is also embedded,” says Director Sami Solanki.

The scientists consider the Sun as a holistic system in order to understand its corona: One group is concerned with the interior of our Sun, where the roots of the activities visible from the outside ultimately lie. In 2009, the balloon- borne telescope Sunrise studied the surface of the Sun with an accuracy never achieved before. Both observers and theoreticians research the corona, and Solanki himself investigates the impact of the Sun’s activity on the Earth’s climate.

Astronomers have long been aware that the temperature on the surface of the Sun is around 5,500 degrees Celsius. The surface is the part of the hot, bubbling ball of gas that we can see with the naked eye. Eighty years ago, scientists began to investigate the corona – the very thin outer atmosphere of the Sun – more closely. To their surprise, they found the temperatures there to be several million degrees. At first glance, this seems as physically impossible as the attempt to get water to boil on a hotplate at a temperature of 50 degrees. But this is what happens on the Sun.

The magnetic field is a powerful source of heat

Gas, at a temperature of one million degrees, emits radiation mainly in the ultraviolet and X-ray ranges. The corona’s light, which can be seen during a solar eclipse, is only a weak glow. Telescopes have to be positioned in space, since our atmosphere absorbs the short-wavelength UV and X-radiation. The US-European observatory SOHO is positioned

1.5 million kilometers from Earth and keeps the Sun continuously in its sight. The images recorded by the various instruments are automated to such a degree that it is possible to view them practically in real time via the Internet.

The solar observers in Katlenburg- Lindau are particularly proud of the SUMER spectrometer (Solar Ultraviolet Measurements of Emitted Radiation); they designed and built most of it and it has performed tireless service since 1996. SUMER disperses the sunlight into its spectral colors, albeit not in the range of visible light, but deep in the ultraviolet, as this is where the corona can be studied particularly well.

“SUMER has played its part in the investigation of many details of the corona’s heating mechanism, because important gas parameters, such as temperature, density and velocity, can be derived from the spectrally dispersed UV light,” says Max Planck researcher Werner Curdt. The experts now agree that the Sun’s magnetic field heats the corona. The only question is how.

The magnetic field is generated around 200,000 kilometers below the surface. In contrast to Earth, where it emerges mainly at the two poles, the surface of the Sun is permeated everywhere with field lines emanating and reentering. The magnetic fields are particularly strong in the dark sunspots. Pairs of these sunspots form the footpoints of a bridge-shaped bundle of field lines emanating from the surface. Two spots thus mark the north and south poles, respectively, of a local magnetic field.

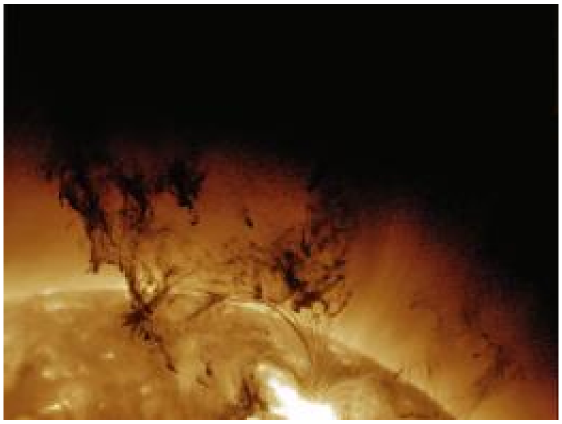
The plasma shoots up in thick plumes

The place of origin for this global, chaotic field pattern is in the hot solar material circulating in the interior. This plasma is electrically conductive and, as it convects, it entrains the magnetic field lines like a teaspoon draws honey, twisting them into thick bundles as it does so. The hot gas of electrically charged particles now flows along these field lines emanating from the surface, and its light makes the lines visible – similar to iron filings lying on a sheet of paper above a magnet and tracing out the field lines. This is how spicules are generated – plumes, with a diameter of around one thousand kilometers, in which the plasma shoots up to altitudes of 20,000 kilometers before crashing down again. Spicules collapse after around 10 minutes and are generated anew at different points. They can be observed particularly well at the rim of the Sun; on satellite images, they are reminiscent of a waving cornfield.

With SUMER’s assistance, Werner Curdt recently discovered that large spicules rotate about their longitudinal axis at speeds of more than 100,000 kilometers per hour – similar to super-tornadoes the size of Germany. “At this enormous speed, the centrifugal force can eject matter from the spicules and catapult it into the corona,” says Curdt. This process would be a conceivable way of keeping the corona supplied with hot matter. A constant supply is necessary because observations show that some of the coronal gas continuously falls back onto the surface of the Sun, while yet more streams away into interplanetary space as solar wind.

“Without the continuous transport of matter, the corona would dissolve within minutes,” explains Curdt. It is thus possible that spicule tornadoes supply the corona with matter. But can they heat the corona to several million degrees, or at least make a contribution? This question still remains unanswered. Although solar research is based on observations, “we don’t want merely to see, we also want to understand,” says Curdt. Jörg Büchner and Hardi Peter’s research group has been developing computer simulations since 2009 in order to provide this understanding of the complex processes.

The complicated and dynamic way in which the magnetic field interacts with the surrounding plasma means that computer simulations of this type are some of the most complex ones astrophysics has to offer. This explains why, for a long time, most modeling calculations could be done in only one dimension. In this case, the computer calculated the temporal development along a magnetic field line in the corona. The scientists have been developing models of selected regions in three dimensions for a number of years.



Such mass ejections are caused by magnetic fields. The fields also provide the energy to heat the corona. Credit: NASA - SDO

A complete simulation may sometimes take weeks or months, even on the most powerful computers. The researchers must apply for the computing time they require, just as their colleagues must submit an application for observation time on a telescope. Even when they have been allotted computing time, a simulation doesn't run through from start to finish, but is always being interrupted for other projects and continued at a later time. "This provides us with an opportunity to check the intermediate results and correct any errors if the computation goes off course," explains Peter.

The solar researcher focuses his simulations on active regions; they differ in size and can best be seen on images in the UV and X-ray range. At any point in time, there are tens of thousands of microflares on the Sun – outbursts of radiation lasting only a few minutes, over an area corresponding roughly to the size of Germany. Ten years ago, the researchers considered the microflares to be hot favorites for the heating of the corona.

Moreover, there are also larger and more powerful eruptions, called flares. They are rarer than microflares, but are spread over a larger area. Within minutes, they release an energy that corresponds to the explosive force of around one billion hydrogen bombs with a megaton of TNT each. Flares occur mainly in conjunction with sunspots.

Field lines twist like rubber bands

The magnetic fields that protrude from the surface as described above lie at the root of all these activities. The Sun now resembles a hot ball of gas whose matter is constantly in motion. Just as water in a saucepan convects, hot gas bubbles up in a convective motion from the interior to the top, where it cools down and flows back into the depths again. "This is why the footpoints of the magnetic loops are not anchored firmly to the surface, but move to and fro as the hot gaseous matter bubbles up," explains Hardi Peter.

The field lines twist and store more and more energy in this process, like a rubber band that is being twisted. If the tension exceeds a critical value, the magnetic field lines can connect with those of opposite polarity. Physicists call this process reconnection. In such a magnetic short circuit, part of the energy stored in the field is suddenly released.

But this is also possible without short circuiting. A magnetic field only has to move to supply energy to the surrounding plasma, very similar to a current-carrying conductor: The moving magnetic field induces currents into the corona, and these currents then heat up the gas they flow through. This is why researchers also call this process Ohmic heating. These processes probably contain the key to understanding coronal heating.

The active regions can be observed very well in the UV range. Quick-motion films impressively show just how dynamic the changes in the magnetic fields and the hot gas are. Magnetic loops swing to and fro, dissolve and form new configurations. The researchers use the SUMER spectrometer to measure density, temperature and velocities. Another of SOHO's instruments provides the magnetic field strengths. Peter feeds his computer program with the observational data of a specific point in time and lets it compute the further development on its own.

Seven-fold ionization of neon causes radiation

After a predetermined period of time, the computation is terminated and the result for all available parameters compared with reality: The program can present the velocity and temperatures fields, or display the appearance of the gas at a specific temperature. Plasma at a temperature of around 700,000 degrees radiates intensely at a wavelength of 77 nanometers (one millionth of a millimeter). This is owed to the neon atoms with their seven-fold ionization.

However, it is difficult to compare the determined velocity fields with reality, because SUMER is too slow. The instrument requires about ten minutes to measure an entire active region. A simulation, in contrast, records the changes once per second over a total period of 20 minutes. “The instruments could be greatly improved,” comments Peter about the current situation.

Another reason that the comparison with reality is not always easy is the fact that the gas is translucent. This is why structures lying one before the other always appear projected onto a plane. This affects the observations, as well as the simulation results. The Solar Dynamics Observatory (SDO), a space laboratory, is currently making this superposition of individual structures clearly visible. Images show the complex spatial structure and the high temporal dynamics in a particularly impressive way here. The Max Planck Institute for Solar System Research has front row seats in terms of the evaluation – after all, it runs the SDO German Data Center.

Some of the phenomena observed can be explained only with such 3-D simulations; the one-dimensional computations did not reproduce them. The agreement between the 3-D models and observations is quite good, for the most part. Hardi Peter recently came across a phenomenon that had been unknown until then in a simulation: At the bottom edge of the computing domain, a gas bubble several thousand kilometers high suddenly formed and shot up abruptly, flying through the corona on a wide arc up to an altitude of 20,000 kilometers before falling back to the surface after 15 minutes. This scene in the film conjures up an image of a dolphin jumping out of the water.

In a more detailed analysis of this sequence, Peter noticed that the magnetic fields happened to be strongly interlaced at the point where the bubble jumped off. They also moved very rapidly and heated their surroundings particularly strongly. Material was now ejected and flew in a high arc into the corona, reminiscent of an explosion. Peter initially assumed this phenomenon, which occurred only in the computation, to be an error, as can occur in numerical simulations. However, the data analysis quickly showed that this was not the case. At a conference, it turned out that colleagues had observed a similar phenomenon and called it a rabbit, because it reminded them of the hopping animal.

New observatory to also monitor the poles

“The interesting feature in this case is that the process could possibly be important on much smaller scales, as well, with spicules, for example,” says Peter. This will be the task of future work with numerical models that have higher spatial resolution and the further comparison with observations.

After many decades of coronal research it is now agreed, beyond a doubt, that, fundamentally, the magnetic fields supply sufficient energy to heat the corona. Peter qualifies this: “But we still don’t know how this energy is transferred to the coronal plasma on the centimeter or meter scale.” Even his simulations can’t clarify this, because they compute the events on large scales of hundreds of kilometers. The solar researchers are in a similar situation to meteorologists: although their models can predict where it will rain with a certain probability, they can’t compute the drop formation in the cloud.

The researchers are pinning great hopes on a new solar observatory, the Solar Orbiter, which the European Space Agency ESA decided to build in the fall of 2011. The space telescope will be launched in 2017 and will orbit the Sun on an elliptical trajectory at a minimum distance of 42 million kilometers. This corresponds to less than one-third of the distance between Earth and Sun. Never before has a space laboratory come so close to our Sun. Furthermore, the orbit will be so strongly inclined with respect to the solar equator that it will also be possible to observe the Sun’s poles for the first time.

Heavy bombardment with flare particles

The Max Planck Institute in Lindau is involved with four of the ten scientific instruments. The institute is supervising the development of a magnetograph that will measure the magnetic field and the plasma velocity. Moreover, a spectrometer based on the experience gained with SUMER will investigate the corona with unparalleled accuracy and very high temporal resolution.

The scientists don't have much time: They have to deliver the instruments to ESA in 2015. And before they do, they must perform lots of experiments – "For example with materials and optics that survive the very high temperatures and very heavy particle bombardment from the solar wind and flares," explains Eckart Marsch, one of the initiators of the Solar Orbiter. The observatory will come so close to the Sun that the space probe's heat shield will reach 500 degrees Celsius.

At this close distance, it will also be possible to measure the original properties of the particles in situ, and in the precise same state in which they come from the surface of the Sun and fly off into interplanetary space along the magnetic field lines. One of the aims is to calculate the trajectories of the particles back to their origin on the Sun, in order to gain a better understanding of how waves and turbulences propagate in the solar wind.

This would enable the researchers to study the close interaction of the plasma with the active magnetic field of the Sun and its heliosphere. This data would then be incorporated into the 3-D modeling of the particle propagation. "One of the main motivations behind the Solar Orbiter is to understand the microphysics of the corona," says Marsch, who is looking forward to a golden age of solar research.

Provided by Max Planck Society

Citation: The Sun's crowning glory (2012, May 11) retrieved 18 July 2024 from https://phys.org/news/2012-05-sun-crowning-glory.html