Sunspots and their cycles

Research from the group of Arnab Rai Choudhuri

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Preamble

More than 99% of the material in the Universe exists in the plasma state—often called the fourth state of matter. The Sun, our nearest star, is an enormous plasma laboratory in which we observe many puzzling plasma phenomena. In 1844 Schwabe, an amateur German astronomer, discovered that sunspots appear on the Sun's surface in a cyclic fashion. The number of sunspots seen on the Sun waxes and wanes with a period of about 11 years. When Hale discovered in 1908 that sunspots are regions of concentrated magnetic field (typically 0.3 Tesla—about 10,000 times stronger than the Earth's magnetic field), it became clear that the cycle of sunspots is actually a magnetic cycle of the Sun.

In order to understand how sunspots form or why we have this magnetic cycle of 11 years, one has to study various complicated plasma processes inside the Sun. This is done by combining the equations of fluid mechanics with Maxwell's equations of electrodynamics. This combination of equations is known by the tongue-twisting name *magnetohydrodynamics*, abbreviated as MHD. The foundations of MHD were laid down in 1940s by scientists like Alfven, Cowling, Chandrasekhar and Elsasser. Then, in a seminal paper in 1955, Parker used the MHD equations to demonstrate a plasma process known as the dynamo process by which magnetic fields can be generated in astronomical bodies. We now know that magnetic fields are found in all kinds of astronomical systems—in planets, in stars and in galaxies. The dynamo process is believed to be responsible for the generation of most of these magnetic fields.

One of the main thrusts of research done in our group is to make theoretical models of various aspects of sunspots and their cycle. We describe below some of the highlights of our research. A graduate textbook on astrophysical fluids and plasmas written by me (Arnab Rai Choudhuri 1998, *The Physics of Fluids and Plasmas: An Introduction for Astrophysicists*, Cambridge University Press) is used in many universities around the world.

The formation of sunspots

Since a magnetic field exerts a pressure, a region of plasma with a magnetic field in it expands due to this pressure and can become lighter than the surroundings. As a result, the magnetic field in a plasma can become buoyant, as conjectured by Parker in 1955. The magnetic field of the Sun is produced in its interior by the dynamo process and then rises to the surface due to this magnetic buoyancy,

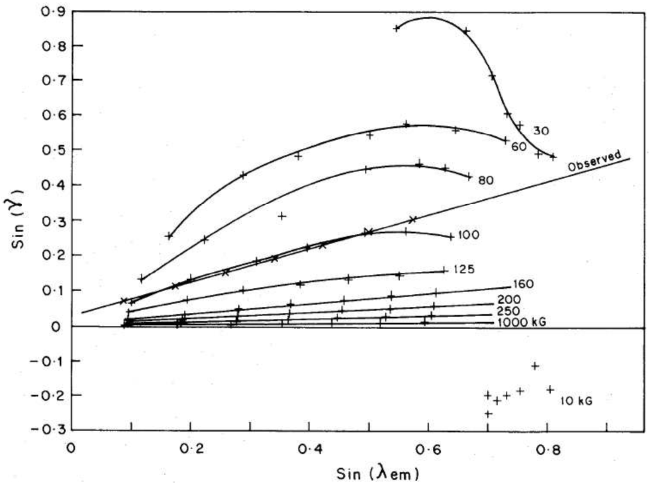

Figure 1: The theoretical explanation of Joy's law, reproduced from D'Silva and Choudhuri [1]. The tilt γ of the sunspot pair is plotted against the emergence latitude λ_{em} on the Sun's surface where the sunspot pair appeared. The straight line gives the median of the observational data. The various curves are from numerical simulations obtained by assuming different values of magnetic field in the solar interior. The assumed value of the magnetic field is indicated (in kilogauss, which is 0.1 Tesla) next to each curve. It is clear that the theoretical curve for 100 kilogauss or 10 Tesla matches observational data well.

ultimately producing the sunspots seen on the Sun's surface. We have to study the buoyant rise of the magnetic fields in the Sun to explain many properties of sunspots. Since the basic equations are quite complicated, these studies are done through numerical simulations. Our group was one of the first groups in the world to carry on such simulations.

Sunspots very often appear in pairs, one of them having positive magnetic polarity and the other having negative magnetic polarity. The line joining the centres of the two sunspots is usually found to be nearly parallel to the Sun's equator. However, Joy discovered in 1919 that sunspot pairs tend to have a small tilt rather than being exactly parallel to the Sun's equator and this tilt increases with the latitude of the sunspot pair. This important observational result is known as *Joy's law.* My PhD student Sydney D'Silva and I studied how the magnetic fields rising in the interior of the Sun get deflected by the Coriolis force arising out of the Sun's rotation. Based on our numerical simulations, we were able to give the first quantitative theoretical explanation of Joy's law in 1993, nearly three-quarters of a century after its discovery [1]. Our calculations showed that theory matches observations only if the magnetic field in the solar interior is assumed to be about 10 Tesla. This is the first time that the value of the magnetic field in the solar interior could be established. This puts some stringent constraints on the dynamo process by which the magnetic field is produced in the Sun's interior. Figure 1 reproduced from D'Silva and Choudhuri [1] shows how our theoretical simulations explained Joy's law and constrained the value of magnetic field in the Sun's interior.

Models of the Sun's magnetic cycle

Many scientists developed models of the Sun's dynamo in 1970s and 1980s. These models suggested that the maximum value of the magnetic field in the Sun's interior can be at most 1 Tesla. As already mentioned, D'Silva and I showed in 1993 that the magnetic field in the solar interior must be about 10 Tesla. Our result was soon confirmed by several other groups. It became clear that the existing models of the Sun's dynamo could not be correct, since these models could not account for the strong magnetic field inside the Sun. Finally in 1995 I, working with Manfred Schüssler and Mausumi Dikpati, developed a different type of dynamo model which allows for a much stronger magnetic field in the Sun's interior [2]. This type of dynamo model is nowadays known as the *flux transport dynamo*. Babcock, Leighton and a group in Naval Research Laboratory in Washington had given some ideas of the flux transport dynamo earlier. We demonstrated in 1995 that the flux transport dynamo can give rise to a dynamo wave propagating towards the Sun's equator. This is a primary requirement for any model of the sunspot cycle and our demonstration of this established the flux transport dynamo as a plausible theoretical model of the sunspot cycle. While there may not yet be a 100% concensus, most scientists working in this field now believe that the Sun's magnetic cycle is due to a flux transport dynamo.

The Sun also rotates about its axis like the Earth. However, unlike the Earth which rotates like a solid body, the Sun is said to have differential rotation. This means that different regions of Sun rotate with different angular speeds. For example, a point near the Sun's equator takes about 25 days to go around the axis, whereas a point near the Sun's pole takes more than 30 days. We know that Bangalore is almost directly south of New Delhi and it will always remain so. However, if the Earth's equatorial regions started rotating faster than the higher latitudes as in the case of the Sun, then after some time Bangalore would be south of Kolkata and then would be south of Beijing or Tokyo! It has been found that the Sun always has some waves travelling all over it. The study of these waves is called helioseismology. In the 1990s helioseismology was used to determine the differential rotation (i.e. the distribution of angular velocity) in the interior of the Sun. Since the differential rotation is an important component of the dynamo process, it became essential to build models of the flux transport dynamo by using the differential rotation measured by helioseismology. When this was first tried (by groups in Boulder and Potsdam), the theoretical models did not produce sunspots at the correct latitudes. My PhD student Dibyendu Nandy and I finally showed a way out of this difficulty in 2002 [3]. There is a meridional circulation of matter inside the Sun. We showed that sunspots would form at correct latitudes if this meridional circulation was assumed to penetrate

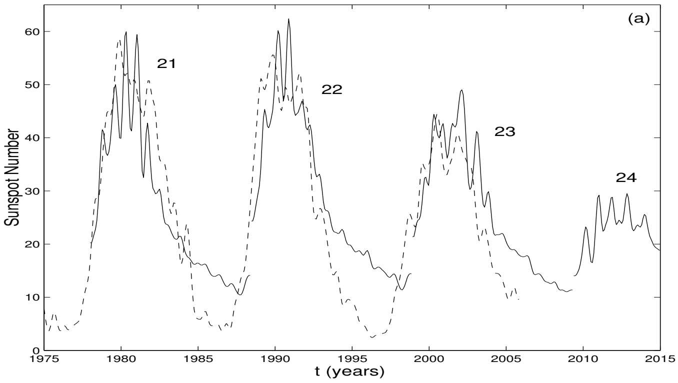

Figure 2: The prediction of the next sunspot cycle, reproduced from Choudhuri, Chatterjee and Jiang [4]. The dashed line indicates the observed sunspot number as a function of time (till 2006 when this paper was prepared). The solid line is the sunspot number calculated theoretically from our dynamo model, extending a few years into the future. Astronomers started counting sunspot cycles from the middle of the 18th century. The last sunspot cycle was counted as cycle 23, whereas the next cycle will be cycle 24.

deeper than what was previously believed. Our work paved the way for building realistic models of the Sun's magnetic cycle based on the flux transport dynamo.

Predicting future sunspot cycles

Not all sunspot cycles are of equal strength. Some are weak and some are strong. When a cycle is near its peak, lots of violent phenomena take place on the Sun, such as solar flares (which are gigantic explosions) and coronal mass ejections (which are huge chunks of hot plasma hurled away from the Sun at enormous speeds). These can affect our lives in different ways—by disturbing the ionosphere which disrupts radio communications, by damaging electronic equipments in man-made satellites and sometimes even tripping power supply grids in large regions (usually in countries like Canada located near the geomagnetic pole). A stronger cycle is more likely to cause these disturbances. Hence it is important to understand why different cycles are of unequal strength and if we can predict the strength of a sunspot cycle in advance. Only now the models of the Sun's dynamo have become sufficiently detailed and realistic to address these questions.

The next sunspot cycle will reach its peak around 2011–2012. Dikpati and Gilman used a detailed dynamo model to predict in 2006 that this next cycle will be the strongest in a long time. To make such predictions, it is necessary to feed some relevant observational data into the theoretical model. When I looked at the observational data carefully, I felt that Dikpati and Gilman, while feeding the observational data, have taken a process to be deterministic which appears random to me. So, along with two PhD students Piyali Chatterjee and Jie Jiang (who was working at the National Astronomical Observatory in Beijing, but did a part of her thesis with me), I decided to calculate the next sunspot cycle from our dynamo model by feeding the observational data differently [4]. Apart from feeding the observational data differently, our model has a diffusion coefficient about 50 times stronger than what was used by Dikpati and Gilman. We predicted in 2007 that the next cycle will be the weakest in a long time. Figure 2 reproduced from Choudhuri, Chatterjee and Jiang [4] shows our prediction. Irrespective of which of the opposing predictions turns out to be correct, the next sunspot cycle will be regarded as a historic cycle in the development of solar dynamo theory, as the first cycle for which detailed predictions were made in advance from dynamo models. We now have to wait for a few years for the Sun-god himself to give a verdict on our debate.

References

[1] S. D'Silva & A. R. Choudhuri, 1993, *Astronomy & Astrophysics* **272**, 621.

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[3] D. Nandy & A. R. Choudhuri, 2002, *Science* **296**, 1671.

[4] A. R. Choudhuri, P. Chatterjee & J. Jiang, 2007, *Physical Review Letters* **98**, 131103 (selected as "Editor's suggestion").