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Living with a Star

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Living with a Star SES Ferreira

We all know our neighborhoods well. Most of us spend the majority of our lives in our homes interacting with others and the environment around us. If we increase the scale we find ourselves as part of a bigger picture, e.g. city, region, province, country and even continent. With different cultural and sporting events we have a pride to associate ourselves with a certain part of our planet. However, if we look on a much bigger scale we all find ourselves living on one planet called Earth. This planet is one of eight (nine minus Pluto) and orbits the Sun in our local solar system. On this scale we have as neighbors Venus and Mars and also the Moon orbiting our planet. Right in the centre is the Sun which contains about 99% of all the mass in our solar system. It is this body of gas which, apart from providing light and heat to our planet, also influences our everyday lives in different ways not always appreciated.

In this work I hope to give a brief overview of our local star concentrating on: the dynamics (e.g. changes over time), how it may influence climate on Earth and how it shields us from the deadly cosmic ray background. I will focus mainly on research done by myself and co-workers. At the end, I will also discuss other stars and how these differ from the Sun and what may happen to them toward the end of their lifetimes.

The Sun is a massive ball of gas held together and compressed under its own gravitational attraction. It consists principally of hydrogen (~90%) and helium (~10%) with a small fraction of other elements. The Sun has a north and south magnetic pole and rotates on its axis. However, unlike the Earth, which rotates at all latitudes every 24 hours, the Sun rotates every ~25 days at the equator and takes progressively longer to rotate at higher latitudes, even up to ~35 days at the poles (e.g. Snodgrass 1983).

Visible on the surface of the Sun are dark, cooler, irregular shape areas called sunspots which have a lower temperature than the surrounding medium. Because of this, it emits much fewer photons and appears much darker. Its lower effective temperature is associated with strong local magnetic fields (e.g. Thomas and Weiss 1992). Detailed records of sunspot numbers have been kept since 1750 and are shown in Figure 1 up 2010.

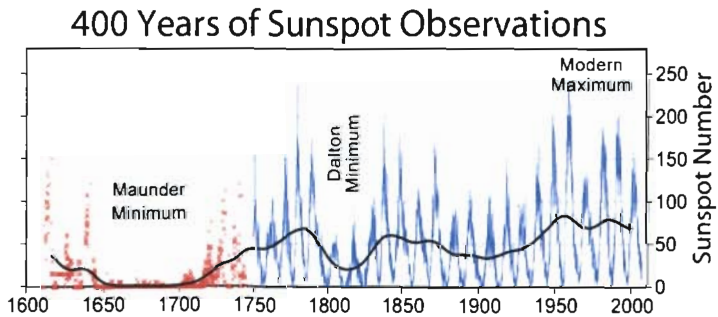

Figure 1 Monthly averaged sunspot numbers (http://en.wikipedia.org/wiki/Sunspots).

The term solar activity can be understood via sunspots. From Figure 1 it is evident that the Sun goes through a period of fewer and smaller sunspots called solar minimum and then a period of more and larger sunspots called solar maximum (e.g. Smith and Marsden, 2003). This rise and fall in sunspot counts is referred to as a solar cycle with the length of cycle approximately ~11 years on average.

Apart from the sunspot variation, the Sun also emits more solar flares and coronal mass ejections toward solar maximum. A solar flare is a large explosion in the Sun's atmosphere releasing a large amount of energy via radiation and particles. These streams of highly energetic particles are hazardous to both spacecraft and astronauts. Flares can also interfere with radio communications. Once these particles enter Earth's magnetosphere they can contribute to the aurora borealis and australis.

Coronal mass ejections originate from active regions on Sun's surface. They are large clouds of charged particles that are ejected from the Sun over the course of several hours and can carry up to ten billion tons of plasma (hot ionized gas). These ejection regions have closed magnetic field lines, large enough in strength to contain the plasma. The field lines must be broken or weakened for the ejection to escape from the Sun.

Energetic particles (either from flares or from coronal mass ejections) can pass through the human body, doing biochemical damage and hence present a hazard to astronauts during interplanetary travel. This radiation is a major concern for manned missions to Mars, the moon, or any other planets. Some kind of physical or magnetic shielding would be required to protect the astronauts. Luckily Earth's atmosphere shields us from most of these highly energetic particles. Interesting, it is believed that the ancient Maya calendar predicts an end of the world apocalypse in 2012 and this maybe due to a large solar flare or coronal mass ejection.

Now the focus shifts to the atmosphere of the Sun. This plasmatic atmosphere is constantly blowing away to maintain equilibrium (Parker 1958). This phenomenon is called the solar wind and is a supersonic flow of fully ionized plasma outward. The wind is composed of approximately ~95% of protons and electrons and other minor ions make up the rest. The solar wind was first proposed by Bierman (1951) to account for the behavior of comet tails which point directly away from the Sun. He found that the pressure of the solar radiation alone could not explain this and suggested that a solar wind exists and effects the formation of comet tails.

There are two distinct types of solar wind speeds. The fast solar wind with speeds up to 800 km/s and the slow solar wind which have typical velocities up to 400 km/s. Figure 2 (from McComas et al., 2000) shows observations of the Ulysses spacecraft showing the latitude dependence of the solar wind speed.

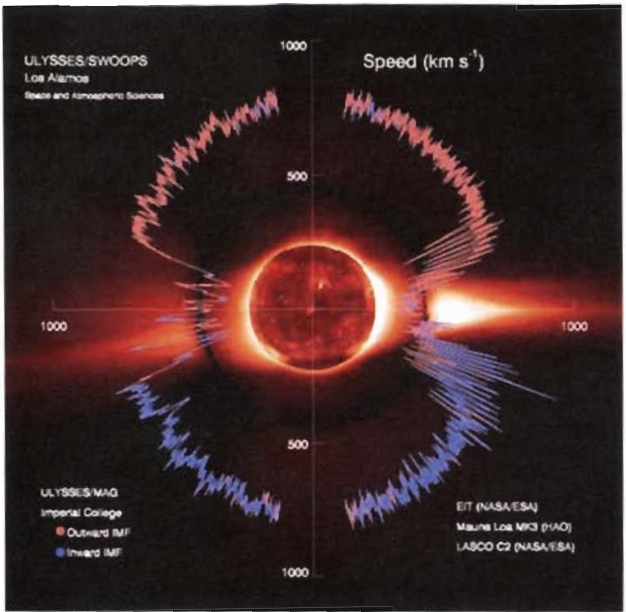

Figure 2: Ulysses observations of the solar wind. For reference, the polar plot is overlaid with the SOHO LASCO/C2 and Mauna Loa MK3 Coronagraph images, and with the SOHO EIT image of the solar disk (from McComas et al., 2000).

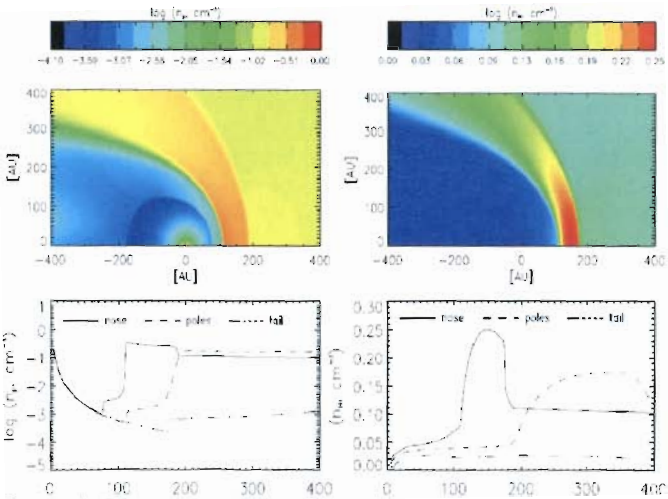

Figure 3: The computed heliosphere. Shown on the left is the solar wind-LISM density and on the right the neutral H density as particles per cubic centimeter. The top panels shows the density as contours in the meridional plane, and the bottom

panels the radial profiles in the nose, poles and tail direction respectively (from Ferreira et al. 2007).

The solar wind extends far out beyond all the planets. This influence sphere is called the heliosphere and is in the order of several hundred AU in size. An AU is defined as the distance between the Earth and Sun. The shape as well as the structure of the heliosphere is mainly determined by three components, which are: the local interstellar medium, the solar wind and the relative motion of the Sun with respect to the local interstellar medium (see e.g. Holzer, 1989). Due to this motion the heliosphere has a bullet-shaped structure with a nose in the upstream direction and tail in the downstream direction.

However, the local interstellar medium is partly ionized with half of it consisting of protons and similar size of hydrogen. This interstellar neutral hydrogen can exchange charge with the protons in the interstellar medium. This leads to the formation of the high density region called the hydrogen wall (See e.g. Zank 1999) in the nose direction.

An illustration of the heliospheric structure in terms of number density is shown in **Figure 3** (from Ferreira et al. 2007). This figure shows multi-fluid solutions of the well known Euler hydrodynamic conservation laws. Shown on the left is the solar wind-interstellar medium proton density, and on the right is the neutral hydrogen density. Both are shown as a function of radial distance. The consequence of the supersonic motion of the heliosphere in the interstellar plasma is the formation of an upstream bow shock, which decelerates and deflects the interstellar charged particles and also a termination shock where the solar wind goes through a transition from supersonic to subsonic speeds.

Also of importance maybe the effect of an interstellar magnetic field on the heliospheric geometry. Opher et al. (2009) suggested that a possible asymmetry due to the interstellar magnetic field. This field is frozen into the interstellar plasma that is deflected around the heliopause. If the angle between the field and the interstellar velocity is not zero, the external magnetic pressure can break the symmetry. An example is show in Figure 4. Shown here are magneto hydrodynamic solutions similar to Figure 3. The trajectories of the two Voyager spacecraft are shown as V1 and V2 respectively. Visible clearly is the asymmetry due to pressure from the interstellar magnetic field.

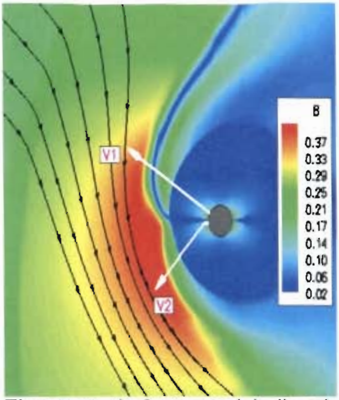

Figure 4: A Computed heliosphere that is strongly influenced by the interstellar magnetic field. The effect of the pressure of the interstellar magnetic field which is larger at the southern than the northern hermisphere is visible (from Opher et al. 2009).

The solar wind carries with it the Sun's magnetic field. This field is dragged into the outer space to form the heliospheric magnetic field. Apart from changing in magnitude over a solar cycle, the polarity of the field also changes during each sunspot maximum. The rotation of the Sun gives the magnetic field a spiral form. An equation of such a spiral was first derived by Parker (1958). It is this field which is frozen into the solar wind which determines the transport of charged particles, like cosmic rays, reducing their intensities significantly compared to outside the solar wind's influence. This process is called the modulation of cosmic rays. If this phenomenon did not occur life on Earth would not be possible. Earth would then be exposed to the full interstellar cosmic ray spectrum. Therefore the Sun, via its influence sphere called the heliosphere including the heliospheric magnetic field, acts as a shield against high energy radiation from outer space.

Next the focus shifts to these high energetic particles called cosmic rays. They travel at nearly the speed of light and arrive at Earth from all directions. Most cosmic rays are nuclei of atoms, ranging from the lightest to the heaviest elements (e.g. Mewaldt 1994). Cosmic rays also include electrons (1%), protons (89%), and other subatomic particles (10%). Cosmic rays are produced by a number of different sources, such as the Sun and other stars, supernova explosions and their remnants, neutron stars and black holes, as well as active galactic nuclei and radio galaxies (see e.g. Forbush 1946; Garcia-Munoz et al. 1973; Axford et al.1977; Bell 1978).

Cosmic rays were discovered by Austrian physicist Victor Hess (Hess 1911) during his historic balloon flights. He found that an electroscope discharged more rapidly as he ascended in the balloon. This proved that this source of radiation is entering the atmosphere from above.

There are recent controversial studies suggesting that cosmic rays influence our climate (e.g. Svensmark 1998). These are based on comparing cosmic ray intensities to the amount of cloud cover over long periods of time. Although not for all periods, there seems to be a correlation for some solar cycles. Also on longer scales, cosmic ray intensities as measured in ice cores seem correlate to e.g. glacier formation and Earth's mean temperature (e.g. Shaviv 2003). However, the detailed physics behind the interaction of cosmic rays with Earth's atmosphere is not fully understood and new experiments are under way to either prove/disapprove this theory.

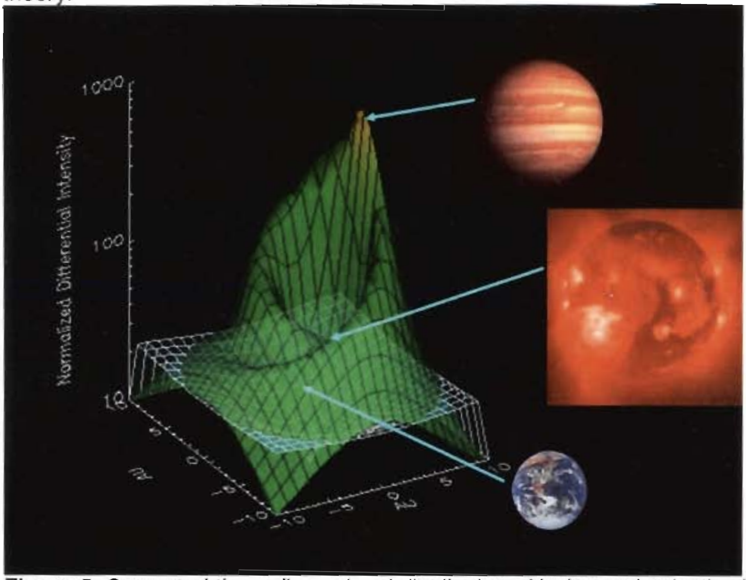

Figure 5: Computed three-dimensional distribution of jovian and galactic electrons in the inner heliosphere.

One of the great accomplishments of the local space research unit at the North-West University over the years was to use numerical models to calculate the cosmic ray background in the heliosphere. First attempts were already done more than 40 years ago and since then these mathematical models have grown in sophistication and valuable contributions were made. As an example I will concentrate what is called low-energy cosmic ray electron modulation (See Ferreira 2002) and present results computed with a numerical model based on solving an appropriate transport equation (Parker 1965).

As discussed earlier, embedded in the solar wind is the Sun's magnetic field wounded up in a spiral and transported with the solar wind into space forming the heliospheric magnetic field. A very unique signature of this spiral can be observed in low-energy electron intensities. At these energies the jovian magnetosphere is the dominant source of electrons (Simpson etal 1974) in the inner heliosphere up to 10 AU (e.g. Ferreira etal. 2001). Shown in Figure 5 are model calculations by Ferreira et al. (2001) showing the three-dimensional distribution of jovian electrons. Signatures of the Parker spiral are clearly visible in the intensities because of the dominance of diffusion along the field lines in the inner heliospheric regions. Found by these studies was that in the inner heliospheric regions jovians dominate their galactic counterparts.

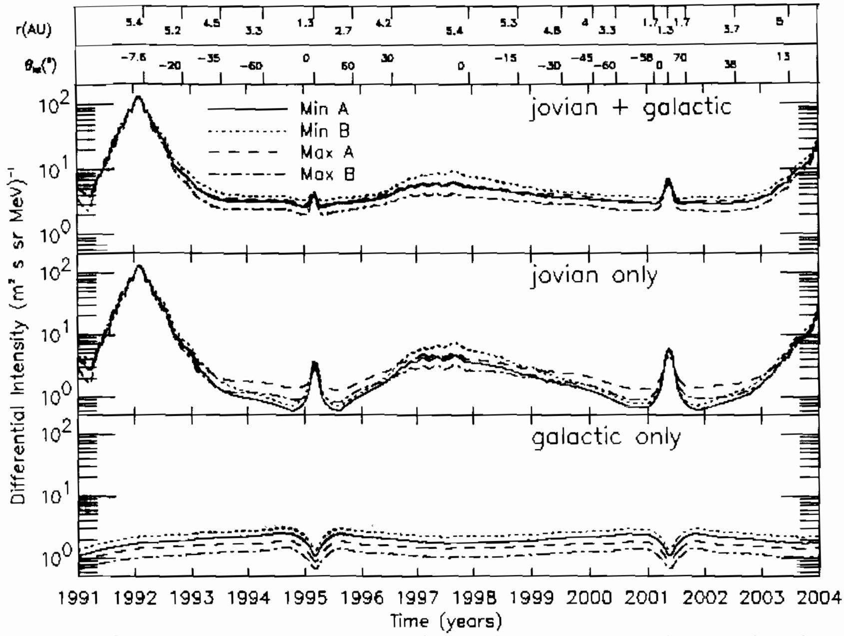

Figure 6: Computed 7 MeV jovian and galactic electron intensity time profiles along the Ulysses spacecraft trajectory compared to Ulysses observations. Top panel shows the combined jovian and galactic electrons, the middle panel the jovians only and the bottom panel the galactic electrons only.

Figure 6 shows another example of theoretical cosmic ray studies. This time model results are compared to spacecraft observations. This figure shows computed 7 MeV jovian and galactic electron intensities along Ulysses trajectory compared to spacecraft observations. Top panel shows the combined jovian and galactic electrons, the middle panel the jovians only and the bottom panel the galactic electrons only.

Shown here is that such a model can be of assistance to get a better understanding and appreciation of spacecraft observations, and to reduce the background noise. The telescope onboard the spacecraft only measure electrons and cannot distinguish between jovian or galactic ones. But with a model the two can be separated and one can provide a percentage as to how many are either jovian or galactic during a specific observation period.

Furthermore, models can also be utilized to calculate the background cosmic ray radiation at all positions in the heliosphere, not just at limited spacecraft trajectories. Apart from understanding the variation of cosmic rays over position and time these studies give a theoretical prediction of what can be expected once long-distance manned spacecraft missions start. It is of crucial importance to know what lies ahead before we set sail to explore these regions because these high energetic particles pose a serious health-risk to potential astronauts.

Now that we have a better understanding of the Sun and its environment we can use our expertise to study other Stars of which evolution greatly differs from our own Sun. By constructing a numerical model and compare results to limited spacecraft observations we have faith in our approach and can extend this to other systems. Although no in situ observations exist outside our solar system we often compare results to different telescope observations.

Stars, such as our Sun does not last forever. The main reason is the constant battle between gravitational collapse and pressure created by nuclear interactions. Once this balance is disturbed gravitation takes over and the star collapses under its own weight. This process is called a supernova explosion and depends on the initial mass of the original star. We can use our modelling expertise to also calculate supernova remnant evolution. A remnant can be classified as the structure resulting from the gigantic explosion of a star in a supernova. The supernova remnant is bounded by an expanding shock wave, and consists of ejected material expanding from the explosion. Inside a supernova remnant we often find a pulsar with an energetic relativistic wind (almost similar to the solar wind) called a pulsar wind nebulae. An example of such modelling is shown in Figure 7.

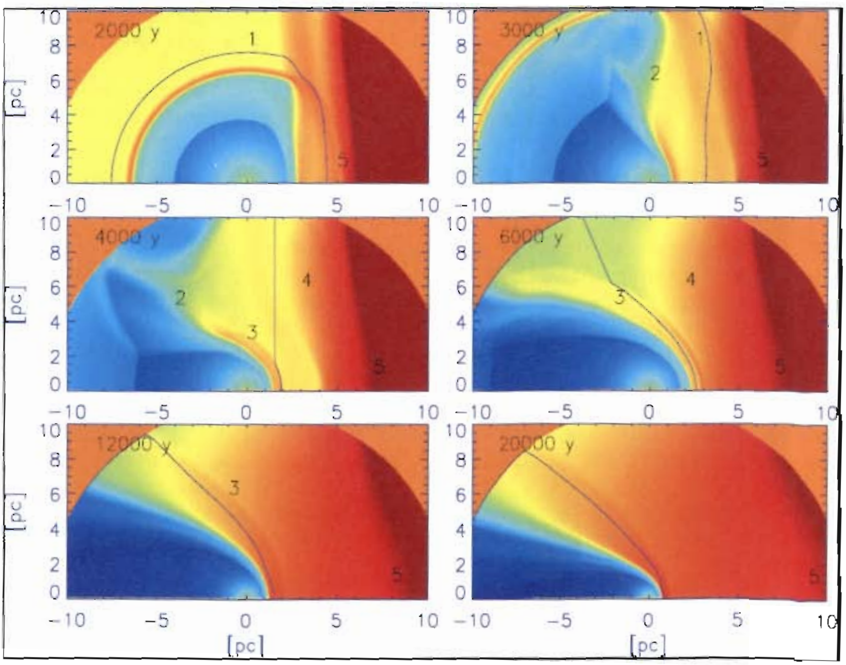

Figure 7 : Model simulations of a the evolution of a supernova remnant-pulsar wind system. The time is shown in the top left corner of each panel. Density is shown as a contour plot on a logarithmic scale. The supernova occurs in an interstellar medium density of 1 particle per cubic centimetre about 5 pc away from a density enhancement of a factor of 10.

Figure 7 shows model simulations of a supernova remnant-pulsar wind system. The time is shown in the top left corner of each panel. Density is shown as a contour plot on a logarithmic scale. The supernova occurs in an interstellar medium density of 1 particle per cubic centimetre about 5 pc away from a density enhancement. Visible in the upper left corner is the forward shock of the supernova remnant, the pulsar wind inside (blue region) and the density enhanced region (dark colours).

Shown here is that as the forward shock hits the more dense region a reflection wave moves back toward the original position of the explosion. This wave drags some of the supernova material with it backwards and moves over the pulsar wind. This causes the bullet-shaped structure. In this calculation the energy of the pulsar is considerable enough, not to be crushed by this reflection wave. As time goes on the pulsar is decreasing in size because a reverse-shock from the original remnant is moving over the relativistic part. The reverse shock originates due to pressure gradients. Also, the energy of the pulsar is decreasing with time resulting in a decrease in size. These simulations can then be compared to telescope observations to considerably increase our understanding of these.

In this work I hoped to give a brief overview of research done by myself and collaborators into understanding the dynamical aspects of our local star as well as other stars. Not only are we interested in the evolution of these over time but also on particle transport in the influence sphere of these. Once these are understood we can get a better understanding and appreciation of spacecraft and telescope observations. Also of importance is how the Sun influence our everyday lives indirectly by contributing to changes in our climate and the radiation environment in space. For all these studies advanced numerical models are needed and we are constantly expanding these to study more detailed physics.

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