IX. What is between the Stars?

The solar wind streams away from the sun with supersonic speed and carries along the sun's magnetic field. On average the sun has also dipole field just as the Earth. The solar wind stretches the dipolar field lines so that there is a separation between the opposite field lines around the sun's equator. This partition between the opposite magnetic field directions drapes around the sun like the skirt of a ballerina. That's why we call this model of the solar wind magnetic field the "ballerina model".

There are several obstacles in the way of this supersonic solar wind, i.e. the magnetic fields (or in other words the "magnetospheres") of the planets like the Earth. In the same way as we hear a supersonic "Boom" when a supersonic jet flies overhead, there is always a "supersonic bang" in a supersonic gas flow across an obstacle, which we call a "shock wave".

The crack of a whip is such a supersonic shock wave, since the tip of the whip goes supersonic. Any obstacle in the solar wind will create such a shock wave, for example the Earth's magnetosphere.

At the bow shock the solar wind is decelerated to just the sound speed. Since the same amount of plasma must flow away from the shock as comes in, the density jumps up at the same time. (This sudden jump in density and pressure is, what causes the bang.)

1. Boundary of the solar system

The same phenomenon is found at the boundary of our heliosphere, but much larger. The interstellar space around the solar system is not empty, and thus the solar wind will be stopped by interstellar material. This is another (and the ultimate) obstacle for the solar wind. Since the solar wind runs at supersonic speed, there must be a supersonic boom out there. We have got another shock wave where the supersonic wind is abruptly decelerated to subsonic speed and the density is abruptly increased.

These shock waves are very efficient particle accelerators in space. We find them around planets and at the edge of the solar system, where we can study them.
Some particles, which cross the shock, get reflected again and again. Since the flow speed varies abruptly, the particles feel the difference every time they are reflected. Think of a tennis game in vacuum. Every time you hit the ball with the bat the ball is accelerated. On Earth it gets slowed down during its flight through the air, in vacuum it would not. The ball would gain energy with every hit. Just this happens at a shock wave with electrically charged particles.

**Fun Physics (Fermi)**

We call this "Fermi acceleration". Such accelerators are found:
- in the solar system
- around planetary magnetospheres at its boundary
- around supernovae

The acceleration can be studied in the solar system at our front doorstep. By deduction we can infer what is going on in the environment of the tremendous shock waves of supernova explosions. Spacecraft have crossed planetary shocks many times. However, no spacecraft has yet reached the boundary of our solar system. So far scientists are still guessing where that might be:

This result is taken from a poll among scientists at a conference on the subject at UNH 7 and 2 years ago. According to this guessing we may expect contact with the termination shock within the next 15 years. The Pioneer and Voyager spacecraft are on their way out.

**2. Interstellar gas in the solar system**

**a) Neutral Gas enters the solar system**

Even though no spacecraft has yet reached the realm beyond the solar wind, we have very recently been able to lay our hands on material from the interstellar gas. There is also neutral gas in the interstellar matter, which blows into our system like a wind, as the sun is moving through the local gas clouds. When this was found in the early 70s this was a stunning discovery. Astronomers thought that all the gas in the vicinity of stars was ionized (i.e. plasma) because of the strong UV radiation. However, the sun is rushing through its neighborhood with a speed of $\approx 20$ km/sec (the speed of the moon rocket). Therefore, there isn't enough time for the solar UV to become effective, and the gas remains neutral up to very close to the sun. It is the same reason, why you don't burn your finger while moving quickly through a candle flame.

Since the solar wind is so dilute (on average gas atoms won't be hit over more than 100 AU) and gas does not feel the magnetic field, interstellar gas flows through the planetary system uninhibited.

Let me tell you a little story on a discovery in which I was involved myself. And this is a quite typical story of such discoveries: You are searching for something, and then you stumble across something else (that might be related though to the object of your search). We had built the
AMPTE satellite to study what happens, if you dump some neutral vapor into the solar wind (like a comet). I have told you about this experiment.

And we had built an instrument, which was able to identify the particles from this vapor when they were accelerated by the solar wind and its magnetic field, namely they are gyrating around the magnetic field lines. In our first experiment we found, listen to this success, 7 of the $10^{25}$ Lithium ions, which we had dumped into the solar wind. Just 7! What a small fraction! Can you imagine, how disappointing this was?

However, sometimes this is your lucky day: by searching for these ions we found something else: Helium, which did exactly the same thing as our Li ions from the vapor cloud! What was this same thing?

Ions can only gyrate around magnetic field lines. Imagine the axis of this wheel to be such a field line. This duct tape represents an ion that has just formed. At this point it has zero speed. Notice: where the wheel touches the ground it does not move with respect to the ground. Otherwise you could buy a new set of tires for your car after every ride. Now the magnetic field moves with the solar wind. See what the dot is doing, it first rests, then speeds up, is fastest on top, then slows down again. This is a quite different motion from the steadily blowing solar wind. All freshly created ions do the same thing!

Therefore, we knew immediately that it had to come from a neutral gas as our lithium. We saw much too much that this could have come from the Earth's atmosphere. Thus the only source was the interstellar gas.

Let me demonstrate, how these ions make themselves known in a little animation of the process:

**b) Neutral gas can be ionized close to the sun**

At the Earth's orbit the solar UV radiation is so intense (intensity varies with $1$/distance$^2$!) that now the neutral gas is turned into ions and electrons and so gets affected by the magnetic field. There are a few more players in the game. Gas can be ionized by

- solar UV radiation
- impact of solar wind ions
- impact of solar wind electrons
c) The new ions will feel the magnetic field

The solar wind takes the sun's magnetic field along on a ride. Thus the field is embedded in the solar wind. Ions can only gyrate around the magnetic field lines. This is like the feet of a gymnast, when performing the giant swing. I have to admit though, I was never able to perform this exercise. Maybe, if I had had a moving horizontal bar coming towards me (like the magnetic field lines in the solar wind), I would have been able. With the help of a moving bar the gymnast is automatically forced into the giant swing. The same thing happens to an ion, which is just formed out of a neutral atom. It gets picked up by the magnetic field, which is convected by the solar wind.

As a consequence, the ions will be swept out of the solar system again with the solar wind. And now we were able to measure these ions! Looking through scientific papers I found that we had found something which many scientists before us had been looking for, but in vain because they didn't have the right instrument. With our time-of-flight spectrometer we could unambiguously identify helium which had only lost 1 electron here. All helium in the solar wind has lost both of its electrons, since it comes from the hot solar corona.

d) The Sun moves with respect to the gas

This was not the end of the interesting story. As I mentioned already, the sun moves through the interstellar gas. This means that the interstellar gas is streaming through the solar system like a wind. The Sun acts as a huge gravitational lens. The gas stream is focused on the downwind side.

Fortunately enough the Earth passes through this region with high gas density on its way around the sun every year in December. With our instrument in Earth orbit we could measure the flux of ions from this gas, and we indeed saw this increase in the density.

This gas behavior can be modeled and we learn from the measurement:

\[
\begin{align*}
\text{from the ion flux} & \Rightarrow \text{interstellar gas density} \\
\text{from the density increase in focus} & \Rightarrow \text{its velocity and temperature}
\end{align*}
\]

The gas in the local cloud has a density of 
\[
\approx 0.015 \text{ He atoms/cm}^3 \quad \text{and} \quad \approx 0.2 \text{ H atoms/cm}^3
\]

This is much less than in the best vacuum we can make on Earth. The temperature is \(\approx 6500\text{ K}\) and the velocity \(\approx 26\text{ km/sec}\).

Meanwhile we can even look directly at the interstellar helium flow.

An instrument on Ulysses can directly detect neutral He atoms, when they run into the sensor fast enough.

3. Gas Between the Stars

In this way we get the information about the interstellar in the immediate solar neighborhood, and astronomers are very excited about this. At a conference last November this interest became very apparent. The methods by which the gas in our neighborhood can be probed are still very difficult to handle. We have to look at the dark lines that are produced by the gas between us and nearby stars, but these are many light years away.
However, already a few light years away the gas looks quite different. View IX.3a

**a) Interstellar Gas absorbs light from stars**

We can observe dark lines in star spectra, which are produced by the interstellar gas between the star and Earth. Slide IX.5
The interstellar gas can be distinguished from the gas in the star's atmosphere through the Doppler effect. The interstellar gas has a different motion than the star.

On the other hand the material between the stars also

**b) Interstellar Gas emits light when in the vicinity of bright stars** Slide IX.6

These visible nebulae are concentrations of interstellar gas as opposed to the relatively thin gas in our immediate neighborhood. The light from these nebulae is seen in emission lines, the gas is not like an incandescent body, as the sun!! Both the absorption and the emission lines can be used to determine the composition of the nebulae. As the stars the interstellar gas mainly consists of H and He.

In addition,

**c) Cold gas emits radio lines**

The most famous radio line is the 21 cm line of non-ionized (neutral) Hydrogen (It has a wavelength of 21 cm). It is so important since there is lots of hydrogen in the universe;

- It is a spectral line we can use it for the Doppler effect and get the velocity of individual gas clouds
- It is a radio emission with long wavelength i.e., we can see through dust

which is of great help when we want to know something about regions where stars are formed, which takes place in dense clouds where we also find a lot of dust.

In order to allow gas to come together and form new stars the gas has to be **cold** (not a lot of motion in it) and **dense** (i.e. there should lots of gravity to keep the gas together). These are clouds with molecules. Since the gas is cold, the molecules don't break apart. In addition, in a dense cloud it is easier to form molecules (2 atoms have to meet for molecule). Slide IX.7

**4. Dust Between the Stars**

**a) Light scattering**

The dust between the stars reveals itself by light scattering: Sketch

![Diagram of light scattering]
b) **Obscuraiton (extinction)**, i.e., it blocks light from stars behind it. This makes observations of very distant stars difficult. We have to take the reduction in light into account, and with light, we can't see very far into the Milky Way.

b) **Reddening:**
However, the effect is stronger for blue light than for red light, which makes the distant stars look more towards the red.

**d) Blue reflection nebulae**

On the other hand nebulae, which are seen in the light reflected from other nearby stars, appear blue. The red light passes through the dust, but the blue light is scattered to the side.

*Radio & IR astronomy: see through dust clouds.*

This is the same physics as we observe in our atmosphere. The sky during the day is blue (shows the scattered sunlight) and sunsets are red. Mountains, which are illuminated by the setting sun, appear red: "Alpenglow".
e) Why is there dust around?

The dust is in

- Cool clouds  - here dust doesn't evaporate.
- Dense clouds  - better chances for molecules to come together.

More dust can be formed. The densest and darkest clouds, such as the so-called Bok Globules (after the astronomer Bart Bok, not Bart Simpson!) are thought to be such places.