The Visible Universe is Mostly Plasma and Mostly Magnetic

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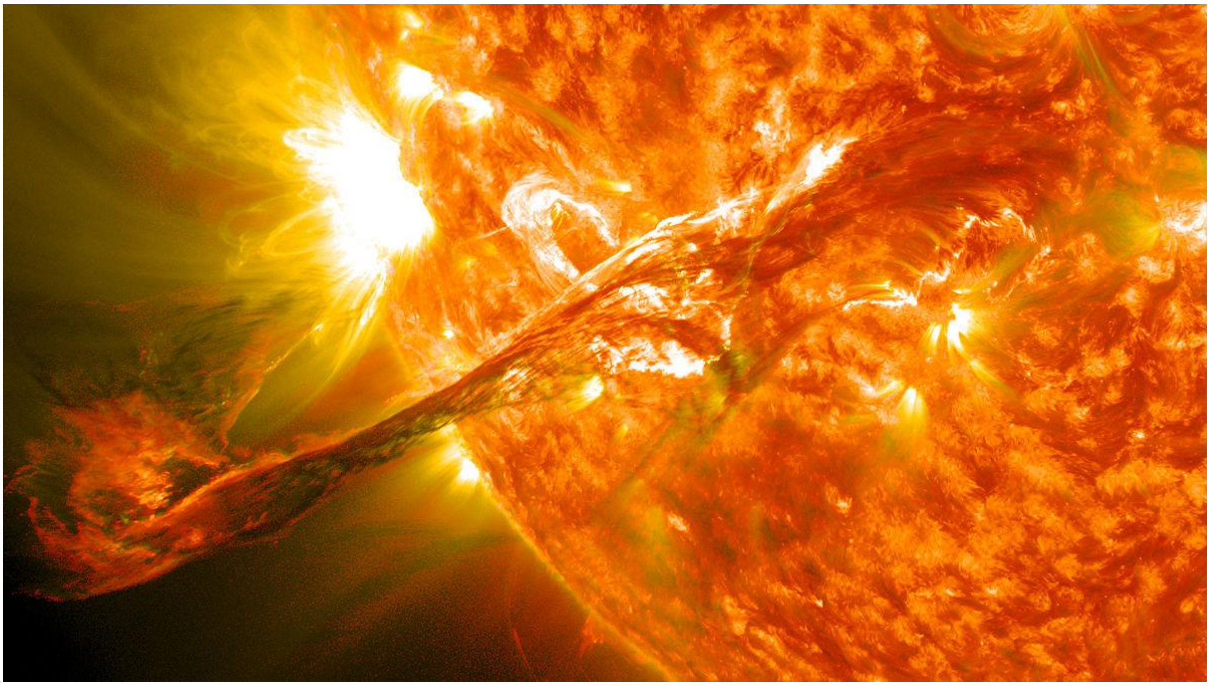
We are taught at school that there are three states of matter: solids, liquids and gasses. In our everyday Earth-bound world that is mostly true, but if we look around the universe most of what we can see is in the fourth state of matter: *plasma*. You cannot understand how cosmic rays get accelerated to high energies and how they travel to Earth (or get deflected in other directions) unless you know a bit about plasmas. The detail is *very* complicated but fortunately even most professional astronomers never have to go beyond some simple analogies that work surprising well in most circumstances.

Plasmas are ionised gases (you get them in neon lights). Stars consist almost entirely of plasmas – about 74% by mass ionised hydrogen (that is a proton and electron moving separately) and about 24% helium (which has two electrons). There are some red stars which are cool enough to allow dust grains to condense far out in their atmospheres but this is a small detail that does not challenge the general picture. (These grains are stuff like carbon and silicates and all the other elements that is part of the 2% of the visible universe that is not hydrogen or helium, and makes the planets - and us. These grains spread into interstellar space and help to cool giant *molecular cloud*s which condense into the next generation of stars and planets.)

When you go out into the daylight you are seeing light emitted by the very hot (~6000 deg C) plasma at the surface of the Sun. In the centre it is much hotter still – about15 million degrees C.

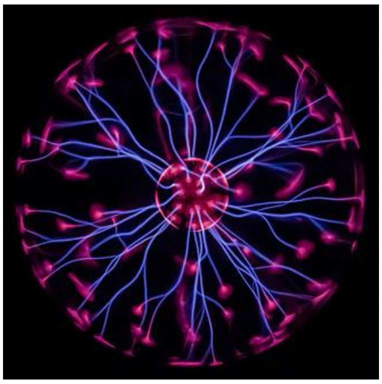


In this image the filaments you can see are plasma concentrations moving along magnetic field lines. The mottled surface of the Sun is caused by convection, which helps wind up magnetic fields.

Negatively charged electrons and positive protons (plus some helium nuclei) mean that electric currents can flow through plasmas, and most astrophysical plasmas have conductivities similar to everyday metals such as copper. In a way this is surprising because even the places we think of as empty space (such as between the Earth and the Sun) are actually filled with a very tenuous plasma – sometimes just 3 or 4 particles per cubic centimetre, sometimes much more - which conducts electricity very well. This is partly because the particles of the plasma are so far apart that they rarely have a chance to bump into each other and dissipate the energy of the electric current. Although the space is pretty empty the electrons and protons can move much, much faster than the electrons in a metal and so can still carry a relatively high current.

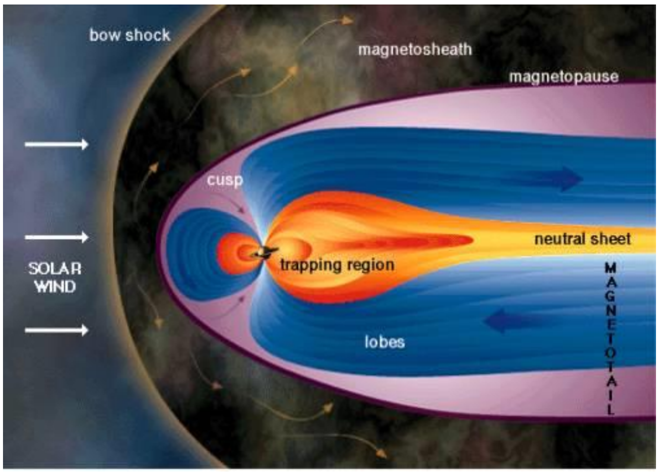
This plasma is coming from the Sun, whose surface is slowly boiling away all the time generating a "Solar Wind". From time to time a big solar flare throws out an exceptionally large ball of plasma known as a *coronal mass ejection* or CME (follow the link for Wikipedia videos). Coronal mass ejections can cause big problems for us on Earth if they hit us square on. Electricity grids can cut out and communications satellites can be severely damaged. (Look up the the "Carrrington Event" for a description of the largest Solar storm on record.) Fortunately, most of them miss us, and those that do not mostly bounce off the Earth's magnetic field, though some of the high energy particles in the CME can find their way down the magnetic field lines at the poles and produce spectacular auroras.

All the interesting behaviour of plasmas comes about because they carry electric currents, which cause magnetic fields, and when you put a magnetic field and something carrying a current together, a force is generated on the material carrying the current, which moves. However, because this is also the material carrying the current, the field changes, which changes the forces on the current……you have probably guessed by now that it becomes very, very complicated to work out what happens in detail. (This is why we have not yet built a working fusion reactor on Earth.)



If you have ever seen a plasma globe at a science museum then you might have an idea of why trying to control a plasma is a bit like trying to pick up a bunch of wriggling snakes. (There is a video of a plasma globe you can watch on this Wikipedia page.) It is this type of behaviour in plasmas that ultimately causes phenomena like solar flares. (See the image above, and the Wikipedia page from which that image is taken and where there is also a good video. What you are watching there is a bundle of tangled magnetic field lines escaping from the hold of the Sun's surface and doing their wriggling snakes act.)

Fortunately for astronomers trying to understand the universe, most of the time we can get away with thinking about plasmas with some very simple ideas and we mostly get things about right as a first guess (though we may have to do complicated computer calculations for the second approximation).



The main rule is this: *magnetic field lines have to move with the plasma through which they thread*. If the magnetic field lines try to move across the material of the plasma then they generate currents which try to make the magnetic field stay where it is.

If a plasma is moving (such as the Solar Wind from the Sun) then the magnetic field goes with it. We say that the magnetic flux is frozen in. So, when the Sun ejects a ball of plasma in a CME it carries its own tangle of magnetic field lines with it. When it arrives at the Earth, the Earth's magnetic field does not want to cross into the material of the CME so the CME bounces away. The picture above shows the Solar Wind flowing around the Earth's magnetic field because it cannot cross the lines of the Earth's field. It also shows that there are radiation belts around the Earth where a few fast moving particles leaking in from the Wind are trapped. Manned space craft and satellites with delicate electronics have to stay away from the most intense of these regions because both people and electronics can be damaged by the radiation. (Google Van Allen Belts.)

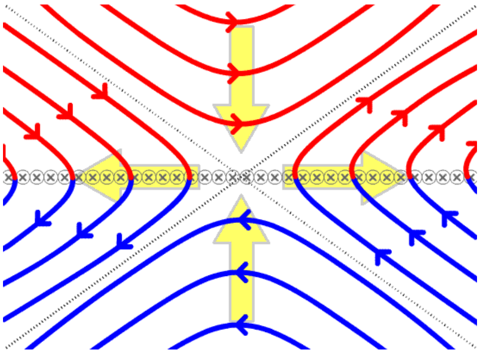
A bounce-off is just the right picture, because we can think of magnetic field lines in plasmas *as if they were elastic bands*. If you try to stretch the plasma along the field lines you will have to do work (and the field is trying to pull the plasma together along these lines). In fact, you can also "twang" the field lines and they will oscillate with plasma waves running along the lines. (If you listen to some older radios that can be tuned to an older very low frequency you can hear all sorts of whistles, cracks and pops that come from waves and bouncing particles in the Earth' field – they used to be called "atmospherics".)

If you try to *compress* plasma *perpendicular* to field lines you will have to do *work* (and the plasma tries to push back perpendicular to the field lines – the magnetic field lines exert *pressure*). This is all just as if you were holding a large bundle of elastic bands, trying to squeeze with your fingers wrapped around the bundle.

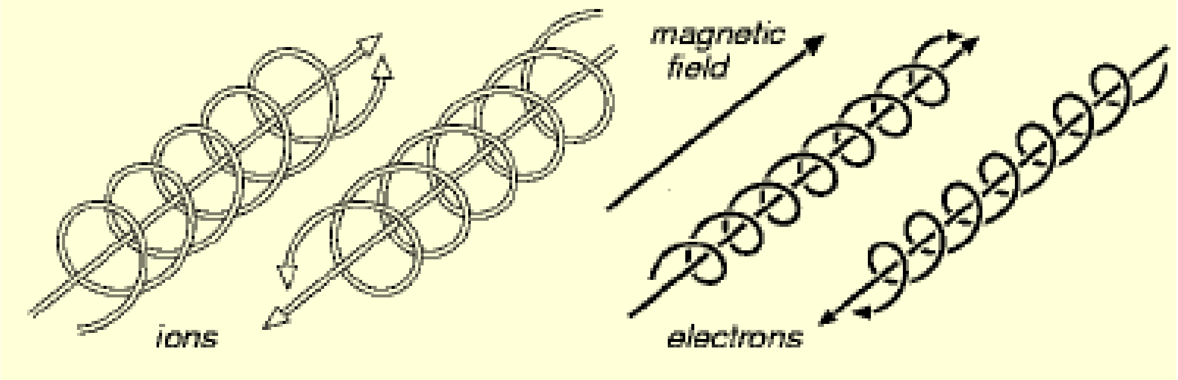
Similarly, if you try to stretch plasma along the field lines you also have to do work, just like stretching elastic bands again, and if you let go the field lines want to snap back.

Hence, if we stir up a ball of plasma and completely tangle the fields up (for example with the type of turbulent motions that happen on the surface of the Sun) most of the fields will be wrapped round and round and round so we get more field lines per unit area. Imagine wrapping an elastic band round a pencil. Each time you go around you layer more lines of force at each point, even though you still only have one band. This is how most magnetic fields in space are amplified from tiny seed fields. It is how the Earth's field is created in the circulating motions of the Earth molten metal core.

All this means that we can store energy in the magnetic fields in plasmas. (Energy is also stored in the hot particles of the plasma, of course.) We can put the energy in by stirring the plasma around (lots of ways to do this, such as heat from the centre of the Sun rising to the surface through convection). We get it out if the plasma expands because on average the tangled magnetic fields exert outward pressure. Remember wriggling snakes: on average they are all pushing against each other. In astrophysical plasmas some of the energy in turbulent motions always seems to get used to amplify initially very small magnetic fields to the point where the energy stored in the field is comparable to the energy in the turbulent motions.



Sometimes we stretch the fields too much and – like the elastic band – field lines break (we say they "reconnect" because magnetic field lines never ever end, but they can decide to switch tracks and join up in different ways). The diagram on the left shows that if we push together bundles of plasma with field running side to side in opposite directions. Magnetic field lines running opposite direction are forced together and they can decide to *reconnect* in the middle with some of the side-to-side field lines not linking up-and-down. Like elastic bands, these can now pull away left and right taking plasma with it (sometimes at very high speed as in solar flares). This release of energy and acceleration might produce some lower energy cosmic rays, but almost certainly not the really very energetic particles. This Wikipedia page has an animation of the above image illustrating what happens in reconnection – but the text and equations are strictly for university level physicists.



We need another bit of physics to understand all this a bit better. We need to think on a microscopic level about the individual charged particles and their interaction with magnetic fields. The force generated by a magnetic field on a wire carrying a current is really due to the forces acting on the individual moving charges in the wire. The force is always at right angles to both the direction of the field and the direction of the current (i.e. the direction of movement of the charges). In space the charged particles are not confined to a wire so the force pulls them around in circles and they whirl around the field lines.

This is why the field lines are fixed in the plasma. A particle can only escape from its field line if it collides with another particle and this does not happen very often when there are only a few atoms in every cubic centimetre. Note that electrons whirl one way and protons (with the opposite charge) will whirl the other way. The protons will also move in a larger orbit because they are heavier, and the higher the speed of the particle the larger the radius of rotation. (Think about swinging a bucket on the end of a rope.)

So we now know that the space between the planets is filled with plasma and is not empty at all. Every other star in the galaxy also has its stellar wind, and sometimes stars explode, so the space between the stars is also filled with plasma. Some of it is very hot and hardly there at all, only a few atoms in every cubic meter, some is much cooler and gets quite dense (by space-science standards – by Earth-standards still a very good vacuum!) with millions of atoms in every cubic centimetre (these are place where stars can start to form). Some of the hottest plasma actually escapes from the galaxy all together, so the space between galaxies is also filled with hot plasma (at perhaps 10^8K) which we can detect with X-ray telescopes. It all conducts electricity and carries magnetic fields.

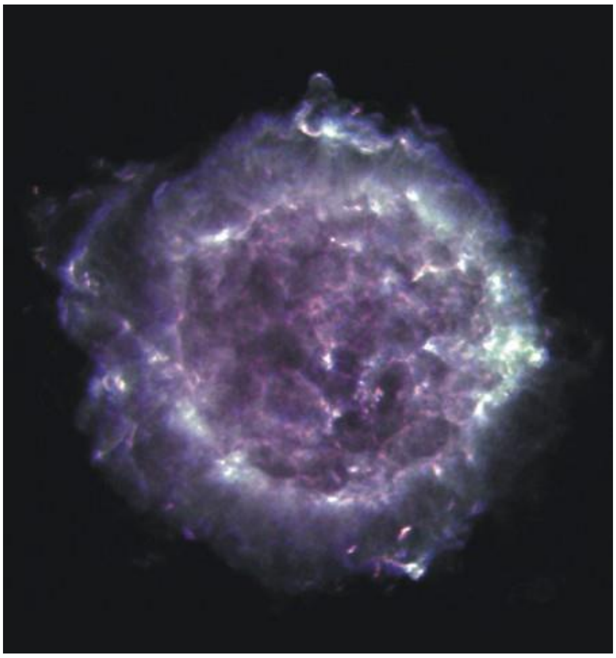
These interstellar fields are not very big – perhaps only 3×10^{-10}T – but they are enough to affect the motion of cosmic ray particles. Even though the magnetic field is very weak the size of the particle gyrations will normally be much smaller than the scale of the galaxy (except for the very highest energies) so they cannot escape from the galactic plane. The whirling motion discussed above also means that the direction from which a particle arrives may not be that from which it started because it may be following curved field lines. Sources pretty much anywhere within our galaxy could be producing the particles that arrive at Earth.

However, as the energy of the cosmic rays gets larger the radius of the whirling circles gets larger and eventually the cosmic ray cannot be confined within the region where the field is located. Particles escape from supernovae remnants when their radius of gyration gets bigger than the remnant. For the very highest energies even the galaxy's inter-stellar magnetic field is not big enough to bend particles around in a small enough circle, so maybe their arrival direction tell us where they come from.

The whirling is the reason we know so much about the high energy particles moving around in space. Whenever you change the direction of a charged particle (give it acceleration) it radiates electromagnetic waves. (The sharper the bend the more it radiates.) For most astrophysical objects these are radio waves and the frequency of the wave corresponds directly to the energy of the particle (hence the scientific importance of radio astronomy). Furthermore they are *polarised* radio waves and the polarisation aligns with the magnetic field direction, so we can work out the direction of the fields in space from looking at the polarisation.

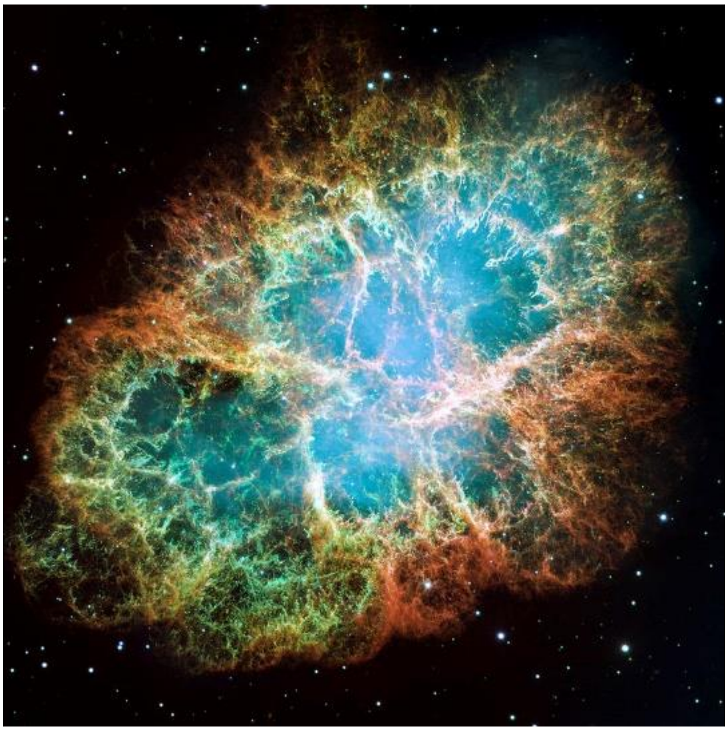
We call this type of emission *synchrotron radiation* because when particle physicists on Earth try to accelerate protons or electrons in high energy physics labs the beams whirling around their accelerators generate this type of radiation. You have to keep putting energy in to keep the beam moving because it loses energy by synchrotron radiation all the time. The more you bend the beam the more it radiates. (That is why the Large Hadron Collider has to be big – the curves can be gentler so you need to feed less energy in to keep the beams going.) The radiation has very characteristic and recognisable properties when we see it coming from the sky so there is rarely any doubt about the way it is being produced, and then we immediately know quite a lot about conditions within the astrophysical object from which they are coming.

We know, for example, that there is weak distributed synchrotron emission coming from the galactic plane, almost certainly due to the cosmic ray electrons confined there by the interstellar magnetic fields. (The arrival rate of electrons at the Earth is just what is needed to produce the radio emission we see.) We can also get a handle on the general circulation of cosmic ray protons because they produce gamma rays when they collide with nuclei in the interstellar medium and this ties up with what we expect.



We can therefore expect that most of the places in space that are producing cosmic rays are probably also radiating synchrotron radiation in the radio spectrum. Let us have a look at some of the radio sources that might also be cosmic ray sources.

Supernova remnants are really good candidates. Cassiopeia A (left) is the brightest radio source in the sky (after the Sun which only looks bright because it is so close). It is the remnant of a star that exploded in about 1680. We know this because we can see it expanding and can project the motion backwards in time. (It is 11000 light years away, behind an interstellar dust cloud so the explosion was not noticed on Earth and we still cannot see it in visible light.) It is about 8 light years across and still expanding at about 6000km a second. What we are seeing with our radio eyes is the expanding shock wave as the material ejected from the star ploughs into the very thin interstellar plasma. It mixes with it in a very turbulent way winding up strong magnetic fields in those bright knots on the image (which emit extremely strong synchrotron radio waves). We therefore know that there have to be very high concentrations of high-energy electrons in these regions. *We are watching cosmic rays in motion when we look at these types of radio source!* (We can deduce that there are lots of high energy protons as well, but these do not radiate so effectively because they are much heavier). They almost certainly escape to circulate as cosmic rays in the galaxy, but can they explain everything we detect on Earth?



The Crab Nebula (left) was a star that exploded in 1054. We know that because it was observed by Chinese astronomers. (Europeans were probably too busy fighting each other to pay any attention to the sky at that time.) It is about 6,500 light years away and about 5.5 light years across. Although the image on the left was made with visible light, it is also a strong synchrotron radio source. The most interesting thing about the Crab is that it should be much less bright than it actually is. Given the rate at which it is radiating away energy, it should have lost most of its brightness in the last 1000 years.

The explanation emerged 1968 when the Crab pulsar was discovered down in the middle. A pulsar is a star made entirely out of neutrons (like an enormous atomic nuclear of about the same mass as our Sun). It is rotating at about 30 times per second. Pulsars can have *huge* magnetic fields. Remember flux freezing – all the original magnetic fields of a star also get compressed down into the pulsar perhaps only 10km across. Rotate these fields at 30 times a second and you have a very powerful dynamo capable of generating enormous voltages which can accelerate charged particles to very high energies. We know this is happening to some extent because we can see that the radio emission from the highest energy particles in the Crab is stronger near the pulsar. The image on the left shows the Crab in X-rays with streams of hot gas coming from the pulsar. Is the Crab pulsar, and other pulsars like it, a strong source of cosmic rays in the galaxy?

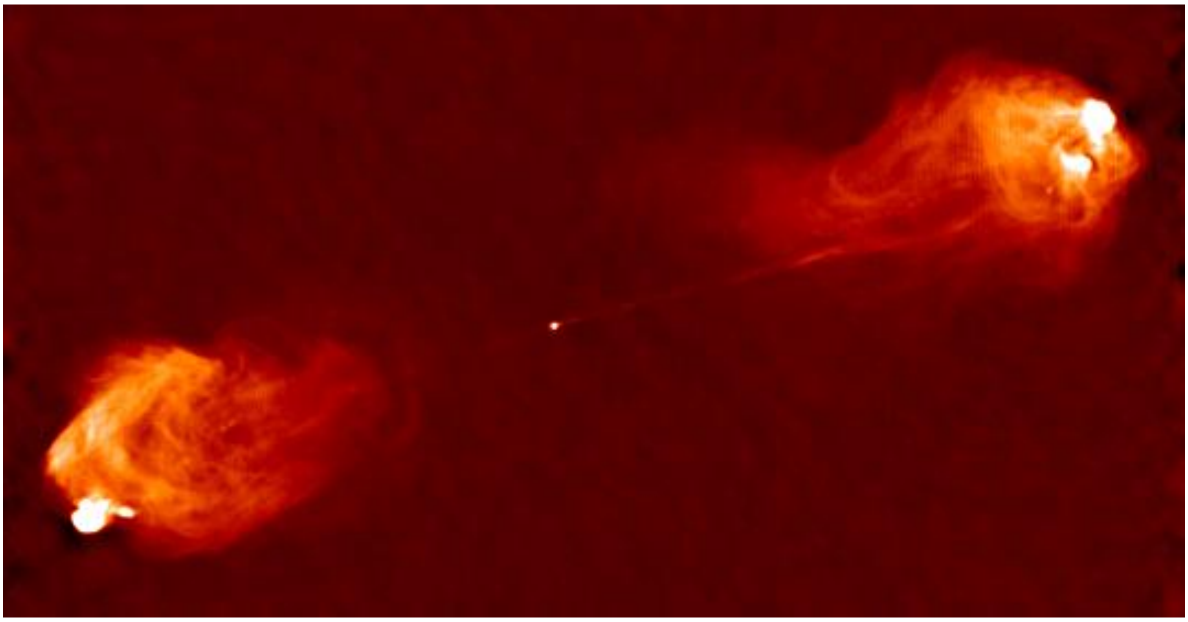
It is possible that the very highest energy cosmic rays cannot be produced in objects like supernova remnants. They are just too small to bounce the particles around until they reach *very* high energies, because, when you are using shock acceleration in supernova remnants the particles need more and more room to make bigger and bigger gyrations as they get heavier and heavier.

Where do we go next? Maybe we have to go outside our own galaxy – which may just be too small to be in the ultra-high energy acceleration game.

The Universe started out as mostly gas, which started to clump together and stars began to form – these made the first galaxies. (We still do not fully understand this process.) Early in their history there is still a lot of free gas around that has not yet made stars and some of it falls towards the centre of the galaxy. We now know that most galaxies seem to have massive black holes at their centre, and they are probably formed at about this time. (We do not fully understand how. Enormous energy releases start as soon as gas begins to sink into an initially black hole, even if it is relatively small, and this should heat all the surrounding gas to such high temperatures that it flies out of the containing galaxy completely.)

Our own galaxy has a black hole at its centre that is certainly more than a million times the mass of the Sun. (We know because we can see stars in the centre orbiting an *invisible* body at high speed.) Some galaxies seem to create super-massive black holes – we have measured some to be over two *billion* times the mass of the Sun by studying the way stars move around near the centre of these galaxies. Early in the history of the universe we have good evidence of many giant black holes – even if we do not know how they are made - with, still, a lot of free gas fall inwards. This is a recipe for exciting events on a scale that leaves even professional astronomers struggling for adequate words of description (giga-ginormous?). When we look out to large distances with radio telescopes we see thousands of powerful radio sources and quasars.

Let us look at **Cygnus A**. This is the second most powerful radio source in the sky (discounting the Sun). However, it is more than half a billion light years away – half a million times the distance to Cassiopeia A, though it looks almost as bright! Hence, the amount of power it is radiating has to be larger by a factor of $10^{10} – 10^{11}$. Here we have lots and lots of energy possibly available to feed into cosmic rays. There are thousands of other radio galaxies similar to Cygnus A – though mostly less powerful, as it is in fact one of the most powerful radio sources in the entire visible universe!



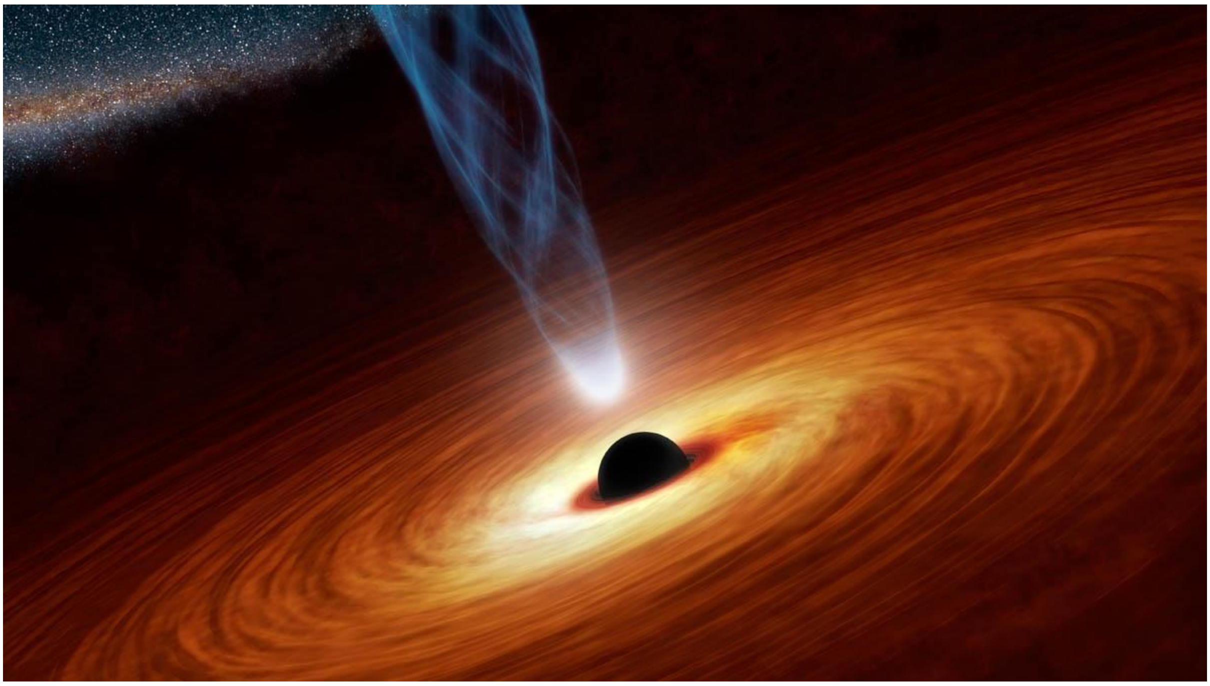
What you are seeing above is a false colour image where the brightness tells you the strength of the radio emissions. The distance between the outer edges of the radio lobes is about 500,000 light years, so it about five times the size of our entire galaxy and those magnetic field threaded lobes have to be storing vast amounts of energy. It is possible to do a minimum energy calculation to deduce that there must be at least 6x10^{52}J stored in the lobes as magnetic fields and protons (not taking account of protons). At the very least this is equivalent to the entire mass-energy equivalent (MC^{2}) of 3x10^{5} stars with the mass of the Sun. It has been calculated that because of the rate at which the lobes radiate away their energy, they need to be resupplied at a rate of about 10^{38}-10^{39}W, which is *at least* a trillion times the power output of our Sun – or that of an entire galaxy of stars.

Notice the dot in the middle. This emission comes from the region around a **super-massive black hole** (an active galactic nucleus), probably at least a billion times the mass of our Sun. (There is in fact an entire giant elliptical galaxy surrounding the black hole – at least ten times as big as our own galaxy - which is visible with the Hubble Space Telescope, but ordinary stars do not radiate very much at radio frequencies so – apart from the Sun – you do not see them with radio telescopes.)

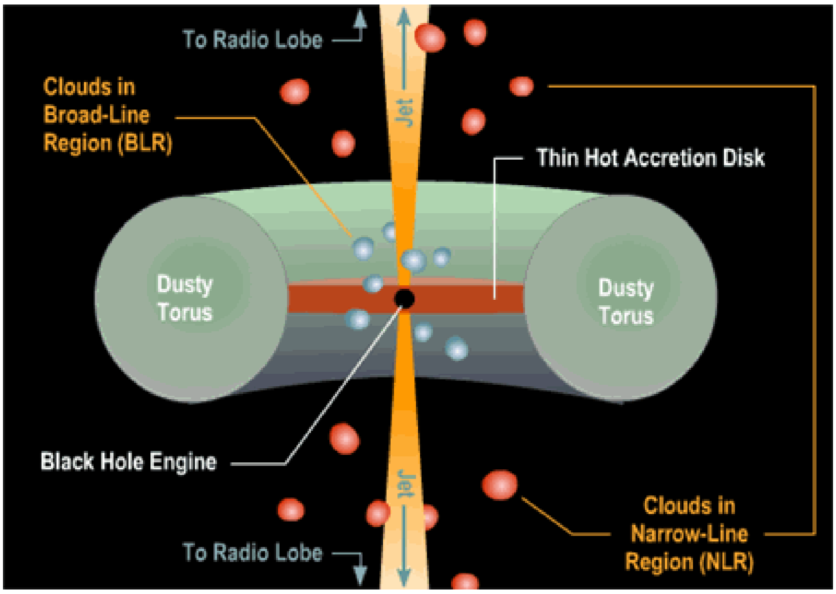
You may also see a couple of lines coming from the centre pointing to the lobes. This is emission from a jet of plasma moving at very nearly the speed of light (we say that it is a “relativistic” jet, meaning Einstein’s Theory of Relativity has to be used to understand its physics). This is what we think powers the outer radio lobes. (We know, for example, that brightest parts of lobes are radiating so much energy each second that they would go dim in only about 10,000 years if they were not resupplied with high energy particles more or less continuously.) The jets blasting into the thin inter-galactic medium stirs everything up and winds up magnetic fields. (The intergalactic medium is very, very tenuous at about 1000 proton/electron pairs per cubic meter but being extremely hot (10^{8}K) it emits X-rays so we know quite a lot about it)

These jets create big shock waves and accelerate high energy particles in the process. You can probably get an idea of the magnetic fields from the filamentary structures you can see in the lobes. In fact, the radio waves are also very strongly polarised which tells us a lot more about the field directions. We think that the jet switches on and off and moves around a bit. The very bright knots in the lobes are probably where the jets impacted the intergalactic medium a little while ago when they were pointing in a slightly different direction.

Astrophysicists are still trying to work out exactly how the jets are produced, but it almost certainly involves winding up strong magnetic fields in a plug-hole whirl as material is sucked into the central black hole. (See the diagrams below.) The jets get accelerated to practically the speed of light so lots and lots of very high energy particles are also probably produced. Remember that what we see when we look with our “radio eyes” *are* high energy particles –cosmic rays. We know they are *there*, can they get *here*?



This is what it might look like down in the very centre of the galaxy. A lot of this is deduction from complex and difficult measurements because it is very difficult to see what is going on from Earth. The larger scale diagram below shows that the central part of the whirlpool is often obscured, and even when it is not hidden, the light from the central part of the *accretion disk* can be so bright (this is a quasar) that we cannot see anything else.



Given how much power is being emitted by sources like Cygnus A, and the energy resupply needed we have seen that staggering amounts of energy are required, but looks just about feasible with a big black hole. (It has to be a black hole because the nuclear fusion process of stars is just not efficient enough – we would need to be using the fusion power of more than an entire galaxy of stars.) Once again, we know that the radio emission comes from synchrotron radiation, which needs very high energy particles.

Down in the centre the light and X-ray intensities are so high that photons bounce off each other – something that probably happens nowhere else in the universe. We have to stretch our physical imagination to previously untried limits in order to explore the processes that may be occurring in this zone.

If these numbers are not making your jaw drop, you have not taken in what I have just said.

Is it possible that the ultra-extreme conditions near the black hole can generate the very highest energy cosmic rays that arrive at the Earth? At first sight it looks a promising possibility.

One problem, however, is that these ultra-high energy rays have to bludgeon aside photons of the universal microwave background in order to travel across the universe. They lose a little energy at each collision and particles from Cygnus A and similar objects should just not get here while still having the very highest energies.

However, if they *do* get here they still carry so much energy (which also means that they get heavy – relativity!) that they will not have been bent much by the magnetic fields in space, so their direction of arrival *might* tell us where they actually came from. If they do come from active galactic nuclei (AGNs) then there should be a clear correlation between their arrival directions and the positions of these ultra-energetic objects. We do, however, need better statistics from these rare arrivals to really tell whether this is so or not.

If HiSPARC data revealed an association between cosmic ray directions and objects like Cygnus A it would be exciting, but it would also be a great puzzle. Scientists like puzzles.

Nature seems to find it easy to create high-energy particles (something we find quite difficult on Earth). We probably do not fully understand why. It may be something to do with the large length scales on which space can work. The types of object we discussed above *may* be enough to account for most cosmic rays.

Some results are suggesting that they are not enough. That is why we need to collect more information from experiments like HiSPARC. Some people think we may need new physics – like “cosmic strings” or exotic interactions involving dark matter or dark energy. Astronomy has been regularly producing big surprises for physicists for the last hundred years – thing we cannot explain without changing our scientific understanding; I do not see why it should stop now.